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Assessment of the Effects of Active Solar Thermal Technologies on Urban Emissions

Energy and Environmental Analysis, Inc.
Arlington, VA

Prepared for

Industrial Environmental Research Lab.
Cincinnati, OH

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AN ASSESSMENT OF THE EFFECTS OF ACTIVE SOLAR THERMAL TECHNOLOGIES ON URBAN EMISSIONS

by

Energy and Environmental Analysis, Inc.
1111 North 19th Street
Arlington, Virginia 22209

Contract Number: 68-03-2622

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16. ABSTRACT

The objective of this study was to analyze the fuel displacement potential of solar technologies to determine if the potential air quality benefits are significant enough to justify the promotion of solar commercialization as an air pollution control strategy. Fuel displacement by solar energy was found to be greatest in the residential water heating market and in electric end-uses in the three AQCR's investigated. Under the more favorable scenarios (high fossil fuel prices and low solar cost), fuel displacement increased substantially, including solar capture of some space heating and industrial process applications.

However, the results of this study suggest a limited role for solar energy in reducing air pollutant emissions. Emissions reductions in all three AQCR's were relatively small, generally less than one percent. The authors cautioned against generalizing these findings to the entire nation, since the report did not evaluate areas that were the most technically compatible with solar systems. Solar systems could readily be a viable emission reduction strategy in a specific case. The increased penetration of solar systems would reduce area source emissions, potentially lowering background emissions in urban areas.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Solar energy, solar energy concentrators, solar heating, air pollution, air pollution control equipment	fuel displacement emissions	Mechanical, industrial, civil and marine engineering air conditioning, heating, lighting and ventilating

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory-Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report presents an assessment of the impact of active solar thermal technologies on emission levels in three Air Quality Control Regions (AQCR): Houston, Chicago and Philadelphia. The objective of the study was to investigate the potential air quality benefits of solar energy due to fossil fuel displacement. The results indicate the energy demand sectors where solar systems may displace fuel combustion in 1985 and 1995 and resulting impact on emissions in those AQCR's. While the quantitative results of this study are specific to three AQCR's, the trends which are identified are general in nature. Researchers should find the approach and results useful when studying solar energy impacts in other locations. For further information on solar energy and its impact on air quality, the Energy Pollution Control Division of the Industrial Environmental Research Laboratory may be contacted.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

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ABSTRACT

Solar energy systems can provide energy without generating the air pollutants associated with the combustion of fossil fuels. This study analyzes the fuel displacement potential of solar technologies to determine how large the reduction of criteria pollutant emissions might be in three metropolitan Air Quality Control Regions (Houston, Chicago, and Philadelphia) which were evaluated for the years 1985 and 1995.

The analysis was divided into five steps: market definiton, technical assessment of solar systems, economic analysis, sensitivity analysis, and emissions impacts. Due to the uncertainties surrounding future solar costs and fuel prices, a range of these costs and prices were tested in five sensitivity scenarios and compared with results of an intermediate ("base case") scenario.

Fuel displacement by solar energy was found to be greatest in the residential water heating market and in electric end-uses in all three AQCR's. Fuel displacement increased from 1985 to 1995 as solar became more competitive with other fuels. Under the more favorable scenarios (high fossil fuel prices and low solar cost), fuel displacement increased substantially, including some space heating and industrial process applications where solar was only marginally competitive under the base case.

The results of this study suggest a limited role for solar energy in reducing air pollutant emissions. Emissions reductions in all three AQCR's due to the expanding market for solar technologies were relatively small, generally less than one percent. However, solar systems may result in significant air pollution reductions for specific cases, such as lowering background pollutant levels by reducing area source emissions. The increased penetration of solar systems would reduce area source emissions, potentially lowering background emissions in urban areas.

This report was submitted in fulfillment of Contract No. 68-03-2662 by Energy and Environmental Analysis, Inc., under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from September 1979 to July 1980 and work was completed as of January 1982.

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CONVERSION TABLE:

EQUIVALENCES OF ENGLISH UNITS AND INTERNATIONAL SYSTEM OF UNITS*

---

1 KJ = 0.948 Btu

1 GJ = 0.948 x 10^6 Btu = 0.948 MMBtu

1 EJ = 0.948 x 10^5 Btu = 0.948 Quads

1 °C = (°F - 32)/1.8

1 m^2 = 10.8 ft^2

1 m^2 = 10^3 hectare = 2.47 x 10^4 acre

1 1/m^2 = 0.0245 gallons/ft^2

---

*The analysis reported here was originally done in English units. The report has been written in the International System of Units (SI) to meet publication requirements of EPA's Office of Research and Development.

APPLICATION OF SI* PREFIXES

Multiplication Factor	Prefix	Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{1}	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

*International Standard Units of Measure.

SECTION 1

INTRODUCTION

OVERVIEW

Solar systems, after their manufacture and installation and excluding back-up components, provide energy while generating few air emissions and other residuals associated with fossil fuel combustion. By displacing fossil-fired sources, solar energy systems could have a positive impact on air quality. Fuel displacement by solar hot water or space conditioning systems in the residential and commercial sectors would reduce area source* emissions and lower background emissions levels. Industrial process steam or heat systems would reduce point source* emissions. Reducing industrial point source emissions might allow expansion in nonattainment areas where industrial growth currently is constrained by provisions of the Clean Air Act.

The objective of this study is to analyze the fuel displacement potential of active solar thermal energy systems to determine how large the solar energy-related criteria pollutant emission reductions in metropolitan areas may be. Solar market penetration, fuel displacement, and emissions impacts are evaluated in two reference years (1985 and 1995) and for three Air Quality Control Regions (AQCR's): Philadelphia, Chicago, and Houston. The maps in Figures 1, 2, and 3 indicate the areas included in these three AQCR's. These regions were chosen because there are data bases of sufficient detail to determine emission reductions from changes in fuel consumption.

TASK PROCEDURE

The analysis performed under this contract was divided into the five sequential tasks which follow:

- Market Definition. The energy base that could be displaced by solar energy systems was identified. The base was subdivided into market segments, each representing a particular combination of energy end use and fuel type. End uses include residential, commercial, institutional and industrial hot water and space heating, as well as industrial process steam. Space cooling was also considered in non-industrial sectors. Fuel types include gas, oil, electricity and coal.

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*A glossary of technical and economic terms used in this report can be found in the appendices.

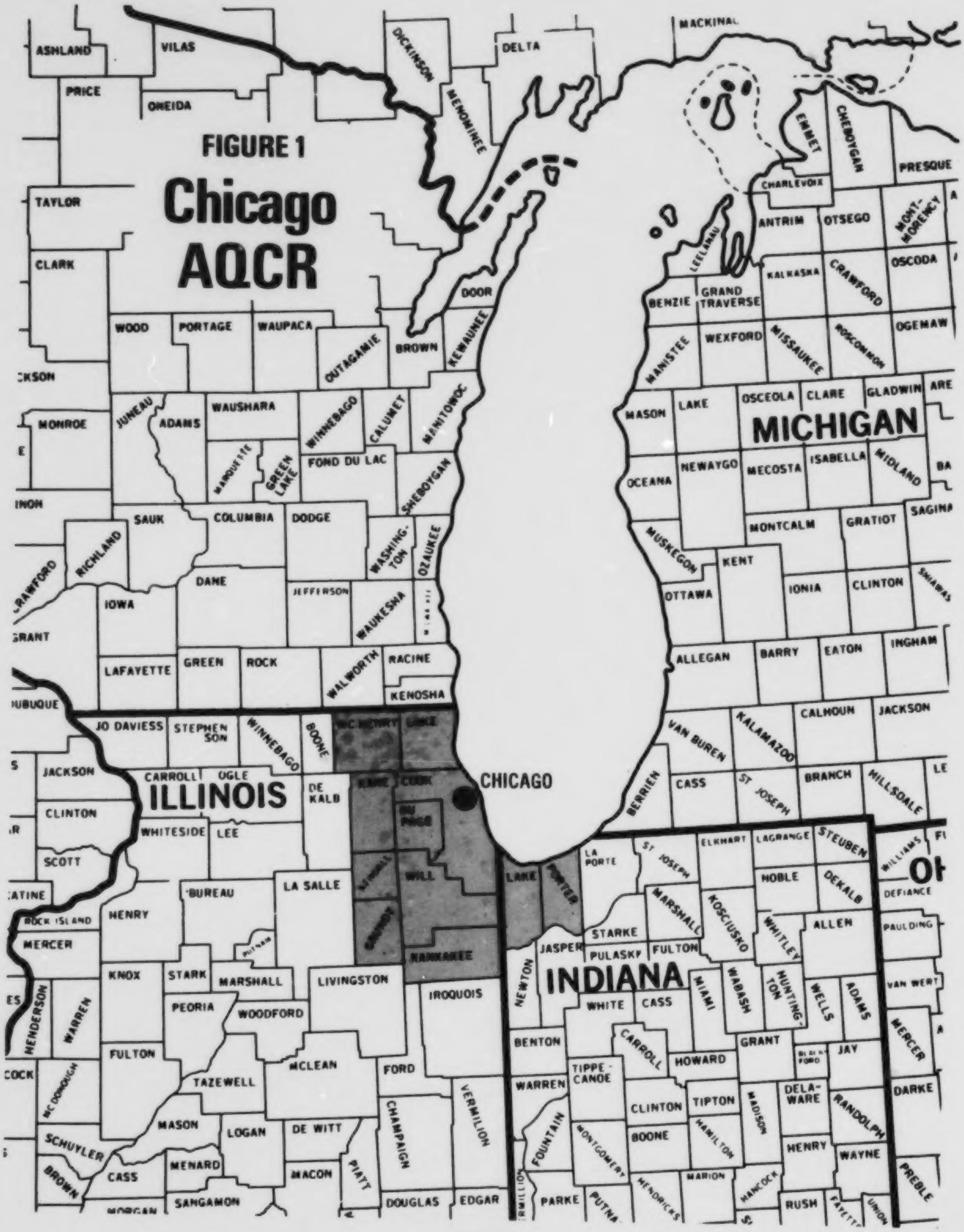

FIGURE 1
Chicago AQCR

ILLINOIS
INDIANA
MICHIGAN
CHICAGO
MC HENRY
LAKE
KANE
COOK
DU PAGE
KENDALL
WILL
GRUNDY
KANKAKEE
LAKE
PORTER
ASHLAND
VILAS
PRICE
ONEIDA
DICKINSON
MENOMINEE
DELTA
MACKINAC
TAYLOR
CLARK
WOOD
PORTAGE
WAUPACA
OUTAGAMIE
BROWN
DOOR
KEWAUNEE
MONROE
JUNEAU
ADAMS
WAUSHARA
WINNEBAGO
CALUMET
MANITOWOC
MARQUETTE
GREEN LAKE
FOND DU LAC
SHEBOYGAN
SAUK
COLUMBIA
DODGE
WASHINGTON
OZAUKEE
RICHLAND
CRAWFORD
IOWA
DANE
JEFFERSON
WAUKESHA
MILWAUKEE
GRANT
LAFAYETTE
GREEN
ROCK
WALWORTH
RACINE
KENOSHA
DUBUQUE
JO DAVIESS
STEPHENSON
WINNEBAGO
BOONE
JACKSON
CARROLL
OGLE
DE KALB
CLINTON
WHITESIDE
LEE
SCOTT
MUSCATINE
ROCK ISLAND
HENRY
BUREAU
LA SALLE
PUTNAM
MERCER
KNOX
STARK
MARSHALL
LIVINGSTON
IROQUOIS
PEORIA
WOODFORD
HENDERSON
WARREN
FULTON
MC DONOUGH
TAZEWELL
MCLEAN
FORD
MASON
LOGAN
DE WITT
CHAMPAIGN
VERMILION
SCHUYLER
BROWN
CASS
MENARD
MACON
PIATT
MORGAN
SANGAMON
DOUGLAS
EDGAR
EMMET
CHEBOYGAN
PRESQUE
CHARLEVOIX
ANTRIM
OTSEGO
MONTMORENCY
LEELANAU
KALKASKA
CRAWFORD
OSCODA
BENZIE
GRAND TRAVERSE
WEXFORD
MISSAUKEE
ROSCOMMON
OGEMAW
MANISTEE
MASON
LAKE
OSCEOLA
CLARE
GLADWIN
OCEANA
NEWAYGO
MECOSTA
ISABELLA
MIDLAND
MONTCALM
GRATIOT
SAGINAW
MUSKEGON
KENT
OTTAWA
IONIA
CLINTON
SHIAWASSEE
ALLEGAN
BARRY
EATON
INGHAM
CALHOUN
JACKSON
VAN BUREN
KALAMAZOO
BERRIEN
CASS
ST JOSEPH
BRANCH
HILLSDALE
LA PORTE
ST JOSEPH
ELKHART
LAGRANGE
STEUBEN
WILLIAMS
NOBLE
DEKALB
DEFIANCE
STARKE
MARSHALL
KOSCIUSKO
WHITLEY
ALLEN
PAULDING
JASPER
PULASKI
FULTON
NEWTON
WHITE
CASS
MIAMI
WABASH
HUNTINGTON
WELLS
ADAMS
VAN WERT
BENTON
CARROLL
GRANT
BLACKFORD
JAY
MERCER
WARREN
TIPPECANOE
HOWARD
CLINTON
TIPTON
MADISON
DELAWARE
RANDOLPH
DARKE
FOUNTAIN
MONTGOMERY
BOONE
HAMILTON
HENRY
WAYNE
VERMILLION
PARKE
PUTNAM
HENDRICKS
MARION
HANCOCK
RUSH
FAYETTE
UNION
PREBLE

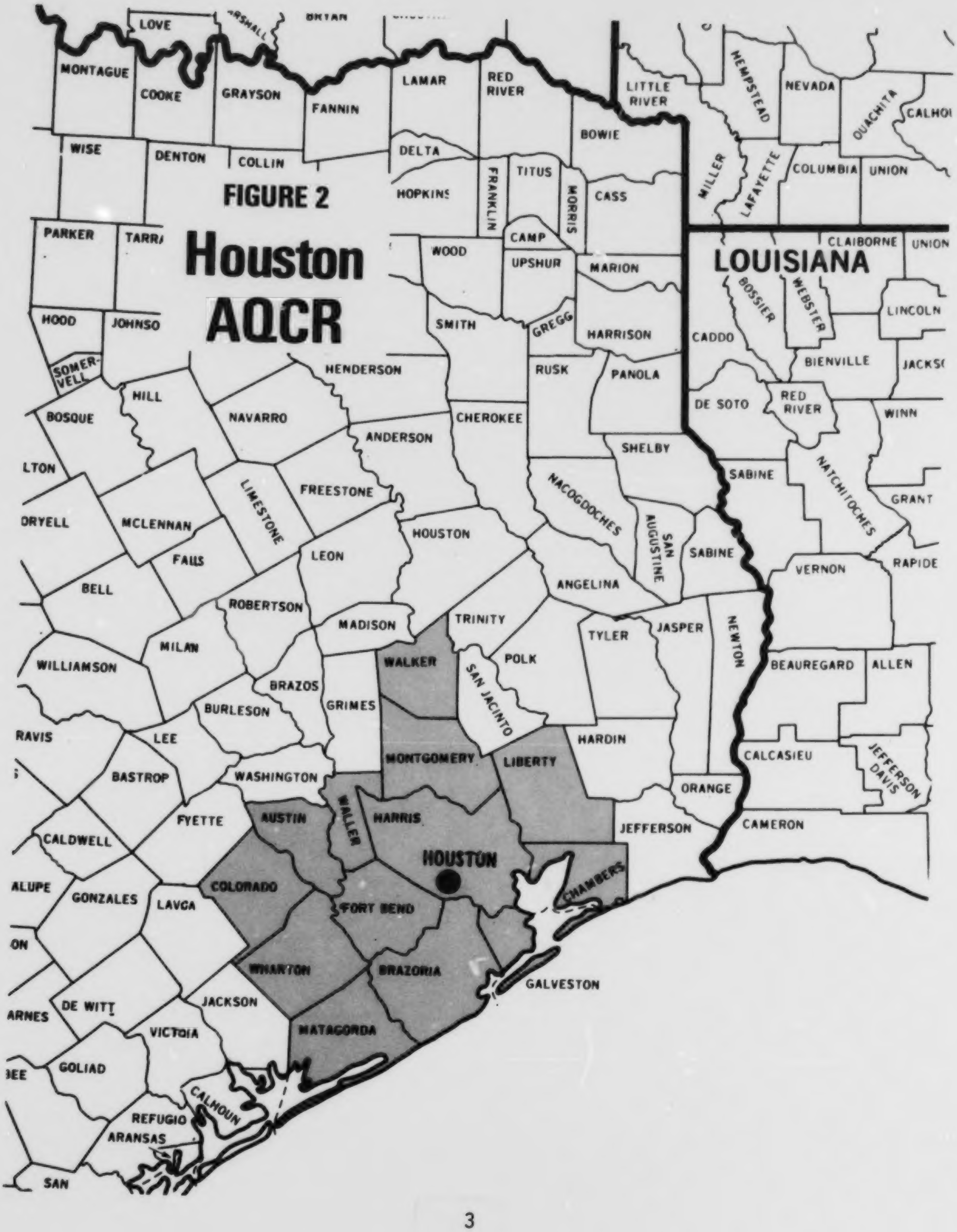

FIGURE 2

Houston AQCR

LOVE
RSHALL
BRYAN
MONTAGUE
COOKE
GRAYSON
FANNIN
LAMAR
RED RIVER
LITTLE RIVER
HEMPSTEAD
NEVADA
OUACHITA
CALHOU
BOWIE
WISE
DENTON
COLLIN
DELTA
HOPKINS
FRANKLIN
TITUS
MORRIS
CASS
MILLER
LAFAYETTE
COLUMBIA
UNION
PARKER
TARRA
CAMP
WOOD
UPSHUR
MARION
LOUISIANA
CLAIBORNE
UNION
BOSSIER
WEBSTER
LINCOLN
HOOD
JOHNSO
SMITH
GREGG
HARRISON
CADDO
BIENVILLE
JACKSO
SOMERVELL
HENDERSON
RUSK
PANOLA
HILL
BOSQUE
NAVARRO
CHEROKEE
DE SOTO
RED RIVER
WINN
ANDERSON
SHELBY
LTON
SABINE
NATCHITOCHES
GRANT
ORYELL
MCLENNAN
LIMESTONE
FREESTONE
NACOGDOCHES
SAN AUGUSTINE
FALLS
LEON
HOUSTON
SABINE
VERNON
RAPIDE
BELL
ANGELINA
ROBERTSON
MADISON
TRINITY
TYLER
JASPER
NEWTON
WILLIAMSON
MILAN
WALKER
SAN JACINTO
POLK
BEAUREGARD
ALLEN
BRAZOS
BURLESON
GRIMES
RAVIS
LEE
HARDIN
MONTGOMERY
LIBERTY
CALCASIEU
JEFFERSON DAVIS
BASTROP
WASHINGTON
ORANGE
WALLER
AUSTIN
HARRIS
FYETTE
CALDWELL
JEFFERSON
CAMERON
HOUSTON
CHAMBERS
ALUPE
GONZALES
LAVCA
COLORADO
FORT BEND
ON
WHARTON
BRAZORIA
GALVESTON
DE WITT
JACKSON
ARNES
VICTOIA
MATAGORDA
BEE
GOLIAD
CALHOUN
REFUGIO
ARANSAS
SAN

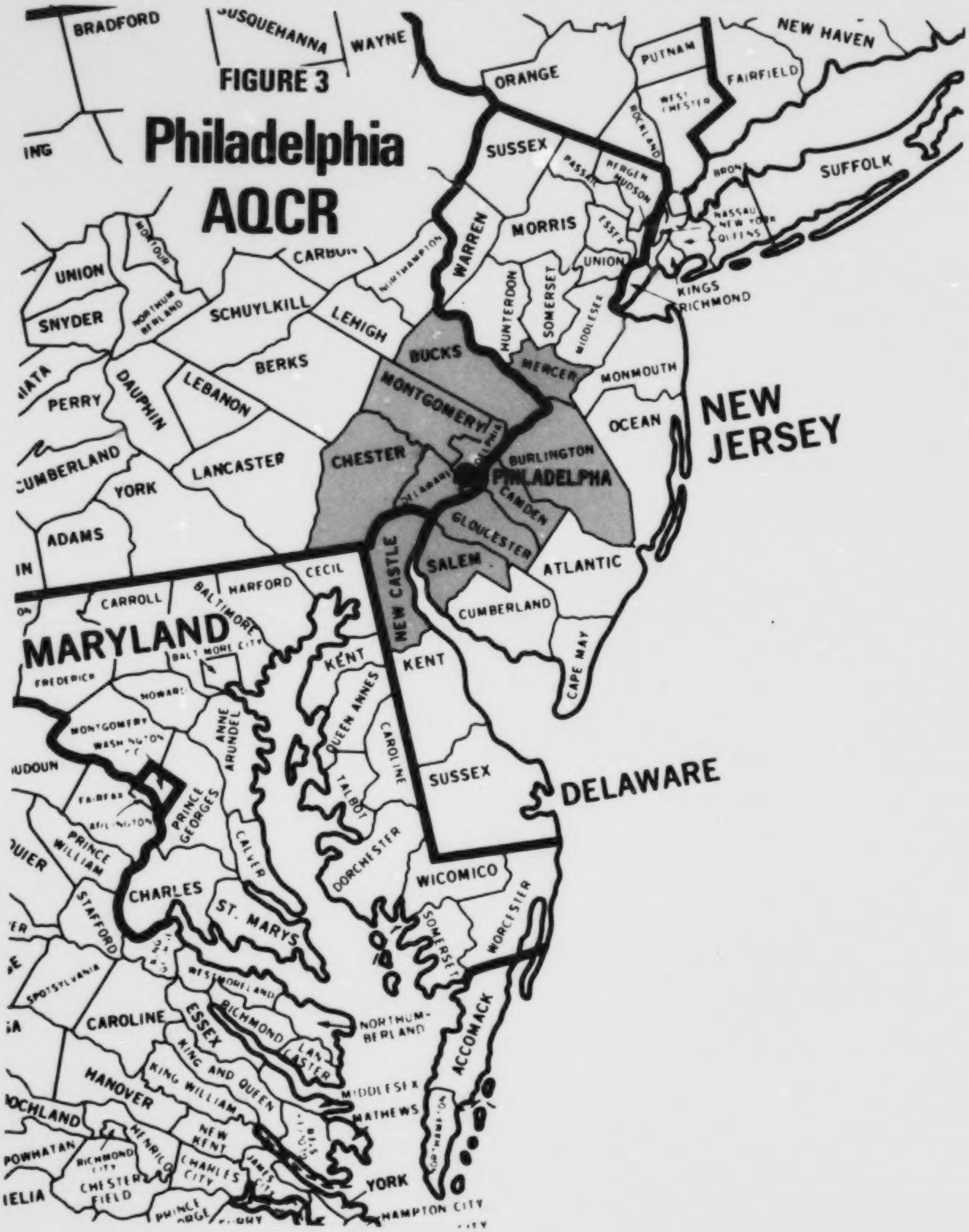

FIGURE 3

Philadelphia AQCR

BRADFORD
SUSQUEHANNA
WAYNE
ORANGE
PUTNAM
NEW HAVEN
FAIRFIELD
WEST CHESTER
ROCKLAND
SUSSEX
PASSAIC
BERGEN
HUDSON
BRONX
SUFFOLK
NASSAU
NEW YORK
QUEENS
UNION
MONTOUR
CARBON
NORTHAMPTON
WARREN
MORRIS
ESSEX
UNION
KINGS
RICHMOND
SNYDER
NORTHUMBERLAND
SCHUYLKILL
LEHIGH
HUNTERDON
SOMERSET
MIDDLESEX
BUCKS
MERCER
MONMOUTH
PERRY
DAUPHIN
LEBANON
BERKS
MONTGOMERY
OCEAN
NEW JERSEY
CUMBERLAND
LANCASTER
CHESTER
BURLINGTON
PHILADELPHIA
DELAWARE
CAMDEN
YORK
ADAMS
GLOUCESTER
NEW CASTLE
SALEM
ATLANTIC
CECIL
HARFORD
CARROLL
BALTIMORE
MARYLAND
BALTIMORE CITY
CUMBERLAND
FREDERICK
HOWARD
KENT
KENT
CAPE MAY
MONTGOMERY
WASHINGTON D.C.
ANNE ARUNDEL
QUEEN ANNES
CAROLINE
LOUDOUN
FAIRFAX
ARLINGTON
PRINCE GEORGES
TALBOT
SUSSEX
DELAWARE
PRINCE WILLIAM
CALVERT
DORCHESTER
CHARLES
ST. MARYS
WICOMICO
STAFFORD
SOMERSET
WORCESTER
SPOTSYLVANIA
WESTMORELAND
RICHMOND
NORTHUMBERLAND
CAROLINE
ESSEX
LANCASTER
ACCOMACK
KING AND QUEEN
KING WILLIAM
HANOVER
MIDDLESEX
MATHEWS
NORTHAMPTON
NEW KENT
HENRICO
POWHATAN
RICHMOND CITY
CHESTERFIELD
CHARLES CITY
JAMES CITY
YORK
HAMPTON CITY
PRINCE GEORGE
SURRY

- **Technical Assessment**. Prototypical active solar thermal energy systems were chosen to represent the typical solar system that would be used to supply a given end use. System size, energy output and performance characteristics were calculated.

- **Economics**. A base case economic analysis was performed for 1985 and 1995. (The base-case scenario used average solar system costs and Series B DOE mid-range energy forecasting (MEFS) projections). Solar costs were compared with the cost of fuel for conventional energy systems for each market segment where solar systems were technically viable.

- **Market Capture and Fuel Displacement**. Market segments where solar systems are potentially economic were identified for the base-case scenario. Fuel displacement was determined by multiplying the energy use within each segment by the fraction of fossil fuels saved by using solar thermal energy. Five alternative scenarios were examined to determine how a range of solar system costs and fuel prices affect market capture and fuel displacement.

- **Emissions Impacts**. Emission reductions within each ACQR were calculated from fuel displacement totals for each sector for the base-case and the best case scenarios. (The best case scenario assumed lower than average solar system costs and a 2% escalation in fuel prices over those used in the base case.)

ORGANIZATION OF THE REPORT

This report is divided into nine sections. The conclusions and findings are presented in Section 2. The recommendations of the project team are found in Section 3. In Section 4, the market disaggregation methodology used in this report is explained. Technical and economic analysis of solar systems can be found in Section 5 and 6. The projected solar market capture and fuel displacement for Chicago, Houston, and Philadelphia is tabulated in Section 7, with the resulting emissions changes reported in Section 8. Uncertainties and potential bias which may be built into the analysis framework and assumptions used in this study are discussed in Section 9.

SECTION 2

FINDINGS AND CONCLUSIONS

The key findings and conclusions from this study relate to: (1) the market capture and fuel displacement of solar technologies, and (2) the emissions impacts of projected solar system development. The factors which influence solar market capture and, therefore, fuel displacement and emissions vary from location to location. The findings and conclusions, therefore, primarily reflect the potential role of solar energy systems in the Chicago, Houston, and Philadelphia AQCR's.

For these metropolitan areas, the emission reductions which can be achieved through active solar thermal energy use in 1995 are quite small (less than two percent) in even the most optimistic case. However, there may be other localities where solar energy use could be more beneficial.

MARKET CAPTURE AND FUEL DISPLACEMENT

Residential, Commercial, and Public Sectors

The results of the base case scenario for the residential, commercial, and public sectors are as follows:

1. In 1985, 95 percent of the total fuel displacement in the three AQCR's resulted from solar systems capturing oil and electric water heating markets.

2. Solar competitiveness and fuel displacement do not differ significantly between AQCR's for hot water heating. (If hot water heating was competitive against a given fuel type in one AQCR, it also was competitive against the same fuel type in the other AQCR's.) Solar competitiveness for hot water heating did not vary greatly between AQCR's because of the similarity in water heating loads and fuel prices in the three metropolitan areas.

3. Fuel displacement increased in 1995 under the base case scenario. Solar systems become competitive with electric and oil space heating in Philadelphia and Chicago and with gas hot water heating in all AQCR's. Space heating systems were less competitive in the Houston AQCR because of the short and mild heating season. (Lower solar system use in Houston per unit of fixed system costs increased the cost per MMBtu used.)

4. Most fuel displacement occurred in the residential sector, because of the size of the residential water heating market and the competitiveness of residential solar space heating systems relative to the commercial and public sectors (e.g., public buildings).

5. Space cooling systems were not competitive under the base case scenario. (See Appendix B).

6. The base case fuel displacement level did not represent a large share of the total AQCR residential and commercial energy consumption. Fuel displaced in Houston, Philadelphia, and Chicago AQCR's represented 1.43 percent, 1.79 percent, and 0.7 percent, respectively, of total residential and commercial energy consumption for 1985. (The Chicago percentage was low because of the small fraction of water heating energy consumption accounted for by oil and electricity, the competitive fuels in 1985). Comparable figures for 1995 were 3.45 percent, 4.94 percent, and 4.33 percent.

7. The low base case fuel displacement reflects the small size of the hot water heating market (particularly for commercial and public buildings) and solar load fractions of 40 to 60 percent. While space heating loads were considerably larger, solar systems were economically attractive in only a limited number of applications, and the economically optimal sized systems only meet a small portion (typically 10-20 percent) of the total building load.

The effects of the other economic-fuel price scenarios are as follows.

1. Solar displacement of electricity increased slightly under the more favorable scenarios. The difference between the base case and the best case (low solar cost, high fuel cost scenario) was greatest in Houston because solar heating systems became competitive under more favorable scenarios.

2. Fuel oil displacement increased sharply in 1985 for Philadelphia and Chicago, with the addition of residential space heat markets under the best case. Fuel oil space heat markets were sizeable, so the capture of space heat markets more than doubles fuel displacement. In 1995, the best case encouraged even more fuel displacement in Philadelphia and Chicago, as public and some commercial space heating applications become competitive. For Houston, residential and commercial fuel oil markets were so small that differences between scenarios did not significantly affect total fuel displacement.

3. Under the base case scenario, no gas was displaced in 1985. However, some hot water heating and some gas space heat markets were captured under the best case in 1985. For Chicago, this increased fuel displacement from 0.0 to 42.9 petajoules (40.7 trillion Btu's). Gas displacement increased in 1995, due to the added capture of gas space heat markets.

4. In the aggregate, for 1985, fuel displacement between the base case and best case increased 223, 843, and 352 percent in Houston, Chicago, and Philadelphia, respectively. These dramatic percentage increases were primarily a function of the small size of the base case solar fuel displacement. The fraction of total commercial and residential energy consumption accounted for in the best case was 3.2 percent, 5.9 percent, and 6.3 percent for Houston, Chicago, and Philadelphia, respectively, in 1985. The gap between Houston and Philadelphia/Chicago was the continued attractiveness of gas heating in Houston under any scenario.

5. In 1995, the change from base case to best case was less pronounced, but the overall fraction of energy displaced in the best case was larger. Total fuel displacement of the best case was 8.6 percent, 10.7 percent, and 8.5 percent for Houston, Chicago, and Philadelphia, respectively.

Industrial Sector

Industries in twelve Standard Industrial Classifications meet the criteria for solar-system technical viability used in this study. These industries are:

- Food and Kindred Products
- Tobacco Manufacture
- Textile Mill Products
- Apparel and Other Textiles
- Lumber and Wood Products
- Furniture and Fixtures
- Printing and Publishing
- Leather Products
- Electric and Electronic Equipment
- Transportation Equipment
- Instruments and Related Products
- Miscellaneous Manufacturing

These 12 SIC's account for 13.7, 14.9 and 0.1 percent of the total non-electrical industrial energy consumption projected in the Philadelphia, Chicago and Houston AQCR's, respectively.

Base case fuel displacement was not significant in the industrial sector. Industrial solar systems are not competitive with any fuel type in 1985. In 1995, solar hot water process applications using water below 100°C (212°F) become competitive with gas and oil in Philadelphia and with oil in Houston. Unlike the residential and commercial sectors, industrial fuel prices vary between AQCR's producing different degrees of competitiveness. (Gas prices in Philadelphia are substantially higher than in Houston and oil prices are higher in Houston and Philadelphia than in Chicago). Base case industrial fuel displacement by solar energy in 1995 in Philadelphia totalled 1.7 petajoules (0.0016 quads), 0.4 percent of total AQCR industrial energy consumption. In Houston, 1.08 petajoules of fuel displacement amounts to only 0.07 percent of 1995 industrial consumption. Fuel displaced in the Philadelphia AQCR is larger in relative terms than for Houston because the potentially displaceable (technically viable) energy base represents a larger fraction of the total AQCR energy consumption in Philadelphia. In Houston, 80 percent of the industrial energy consumption is accounted for by two non-solar viable SIC's, 28 (Organic Chemicals) and 29 (Petroleum Refining).

Four factors account for the relatively low base case fuel displacement levels occurring in the industrial sector for all of the AQCR's: 1) the initial limitation of solar systems to 12 solar viable SIC's, 2) industrial coal use, where solar is not competitive, 3) limited low temperature process-water applications, the only solar competitive application in the base case, and 4) the solar load fraction of 8 to 12 percent calculated as a weighted average between boilers, preheaters, and process applications for the 12 solar viable SIC's.

Industrial fuel displacement increased under the most optimistic scenarios. The change was reflected in competitive gas and oil space heat systems and competitive oil and gas process heat, steam applications, and preheat applications for temperatures up to 816°C (1500°F). However, the additional fuel displacement was not significant relative to the total industrial energy consumption base. Best case fuel displacement in 1985 amounted to 0.9 percent, 1 percent, and 0.1 percent of the total industrial energy consumption base for Philadelphia, Chicago, and Houston, respectively. Best case figures for 1995 for Philadelphia, Chicago, and Houston, are 1.3 percent, 0.9 percent, and 0.2 percent, respectively.

EMISSIONS IMPACTS

The positive emissions impact of active solar thermal technologies was found to be limited given the assumptions of this analysis. There are two primary reasons for this result: 1) fuel displacement was a small fraction of total AQCR consumption and 2) displaced fuels typically involved low emissions (gas, distillate oil, and, to a lesser extent electricity). The fuel displacement by solar systems would cause reductions in emissions from small area sources, particularly in the residential, commercial and public sectors, which would lower background emission levels.

Solar applications were generally most competitive with electric end uses. Electricity has a higher emissions output per unit of usable thermal energy than gas or distillate oil because of the use of coal and the threefold greater fuel input (for fossil fuel generating plants) prior to conversion to electricity. As a result, electricity displacement had the largest impact on overall emissions displacement (this trend was less prevalent in Chicago than in the other AQCR's due to Chicago's large nuclear generating capacity).

The overall impact of active solar thermal technologies on total AQCR emissions in the 1985 base case was less than one percent of total emissions for each pollutant and AQCR investigated. The best case scenario (low solar cost, high fuel price projection) increased emissions reductions by 19 to over 700 percent over the base case. However, under the best case scenario, displacement of emissions in 1985 never exceeded two percent of total AQCR emissions. Even under the more favorable economic scenarios, emissions reductions due to solar displacement of fossil fuel were small.

GENERALIZATION OF RESULTS TO OTHER GEOGRAPHIC LOCATIONS

Four variables are likely to have the most significant effect on emission reductions that can be achieved in an urban areas through extensive use of solar energy. Comparison of the magnitude of these factors with those in the three AQCR's considered in this study will indicated whether more emission reductions could be achieved than were noted here. The range of fuel mix patterns in these three cities span those found in most of the country. However, fuel prices and insolation profiles -- two factors affecting solar system economics -- are not representative of the whole country. Some parts of the country, such as the northeast, have fuel prices significantly higher than the AQCR evaluated; in other regions, such as the northwest, fuel prices are lower (for electricity). The southwest has a much higher insolation rate than the reference AQCR's, while in the northeast, insolation rates are somewhat lower. Finally, state and local incentives can affect the economics of solar energy investments. The use of marginal cost pricing in determining utility rates for fossil fuels and electricity could significantly increase the competitiveness of solar energy. The economics of solar energy investments would also improve if the deduction of fuel costs as an operating expense was eliminated.

SECTION 3

RECOMMENDATIONS

In this study the air pollutant emission reductions due to active solar thermal market penetration were relatively small even under the more favorable economic scenarios. Certain trends are evident from this analysis, however, which suggest the potential for further research and for specific opportunities for solar energy and related emissions reductions.

Recently developed solar technologies (e.g., passive solar, photovoltaics) should be evaluated especially in geographic areas more suited to solar applications. These alternative technologies are rapidly decreasing in cost and are gaining demonstration experience. The combined emissions displacement potential of these technologies and active solar thermal technology could significantly reduce background and/or point source emissions levels.

The potential for using solar thermal energy in other regions of the country needs to be assessed. In particular, areas with high solar insolation, higher fuel prices and/or more government incentives for solar installation should be investigated. In choosing other study sites, the emission rates of displaceable conventional fuels also need to be taken into account, since these rates will influence the size of any potential emissions reductions.

In this report, assumptions were made which limited the size of solar systems which were projected to be used in the future. While it is believed that these assumptions were valid for the three AQCR's considered here, there may be other metropolitan ares where larger systems would be economical. This might, for instance, be the case in less densely populated cities in the southwest. The availability of additional space for solar systems could make solar energy technically viable for some commercial and public applications and for some industrial processes which were not included in this report. The potential for increased solar system size and related emission impacts needs to be investigated.

The air quality benefits of solar energy use need to be determined, based on emission reductions calculated by this, and similar, studies. It will be particularly important to determine how the impacts of solar energy vary with system size, since numerous small fuel combustion sources often have different air quality impacts compared to a limited number of large sources of air pollutants. Also, the current air quality status of metropolitan AQCR's should be investigated to determine how significant the air quality improvements from solar energy are likely to be.

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SECTION 4

MARKET DEFINITION

OVERVIEW

The total energy base in each AQCR was determined on an aggregate level (sector and fuel type) as a first step (see Tables 1 and 2). The aggregate energy base revealed differences in fuel mixes and the relative contribution of sectors to total AQCR energy consumption. The residential and commercial sectors accounted for a larger share of the total energy consumption in the Philadelphia and Chicago AQCR's (68 and 58 percent, respectively, in 1985) than in the Houston AQCR, where these sectors only accounted for 25 percent of the total. Since solar systems are not equally competitive in all sectors, these structural differences affect the degree to which solar systems displace fuel and impact overall emissions levels.

The aggregate energy base was disaggregated into market segments to reflect technical factors (e.g., process temperatures, building design, and performance factors) and economic factors (e.g., ownership status and access to financing) which affect solar competitiveness. The market was further disaggregated by type of structure, end use, and fuel type (see Table 3). The result of the disaggregation process was a multidimensional matrix consisting of 1,467 end-uses and fuel types where solar thermal technologies are potentially competitive. For example, typical market segments in the residential sector would include single-family/detached/electric hot water and multifamily/high rise/ gas space heat. Energy consumption was estimated for 1980 and projected for each market segment in the two reference years, 1985 and 1995.

METHODOLOGY

Residential Sector

As shown in Table 3, each sector was disaggregated into market segments. For the residential sector, the energy consumption for the five housing types indicated was determined as a first step based on the number of housing units in each AQCR for all three reference years. The 1970 Census of Housing, "Detailed Housing Characteristics" (U.S. Bureau of Census, 1973), supplied the baseline housing data for each AQCR. These numbers were updated to 1976 through growth trends from the 1976 Annual Housing Survey (U.S. Bureau of Census, 1978a). Population projections (U.S. Bureau of Census, 1979a) combined with household formation rates from

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TABLE 1. PROJECTED AQCR ENERGY CONSUMPTION, 1985
(EJ/yr)*

City	Fuel	1985 Sector Energy Consumption Residential	Commercial**	Industrial***	Total
Philadelphia					
	gas	0.190	0.058	0.130	0.378
	oil	0.159	0.075	0.031	0.265
	coal	--	0.004	0.129	0.133
	electric	0.055	0.190	0.062	0.307
	Total	0.404	0.327	0.352	1.083
Chicago					
	gas	0.494	0.114	0.331	0.939
	oil	0.062	0.055	0.094	0.211
	coal	--	0.011	0.225	0.236
	electric	0.051	0.208	0.065	0.324
	Total	0.607	0.388	0.715	1.710
Houston					
	gas	0.056	0.042	0.637	0.735
	oil	0.004	0.005	0.215	0.224
	coal	--	0.002	0.134	0.136
	electric	0.045	0.110	0.085	0.240
	Total	0.105	0.159	1.071	1.335

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* 1 EJ = 0.948 Quads = 0.948×10^{15} Btu

** Includes public sector consumption. The public sector accounts for from 14 to 23 percent of the sector total, depending on the AQCR and year. The commercial sector is comprised of SIC numbers 50 through 99.

***The industrial consumption total includes only the manufacturing SIC's 20 through 39. Excluded subsectors (mining, construction, and agriculture) account for approximately 12 percent of total industrial consumption (as a national average).

Note: Sector differences are a function of the relative size of the sector (e.g, the disparity between the disproportionately small size of Houston's residential and commercial sectors and the enormous size of Houston's industrial base). Energy use efficiencies within sectors are fairly constant across region and contribute only slightly to the variation indicated.

SOURCE: Resources for the Future. 1979. Energy in America's Future. Johns Hopkins University Press. Baltimore.

TABLE 2. PROJECTED AQCR ENERGY CONSUMPTION, 1995 (EJ/yr)*

City	Fuel	1995 Sector Energy Consumption			
		Residential	Commercial**	Industrial***	Total
Philadelphia					
	gas	0.185	0.071	0.150	0.406
	oil	0.141	0.085	0.023	0.249
	coal	--	0.003	0.159	0.162
	electric	0.054	0.250	0.073	0.377
	Total	0.380	0.409	0.405	1.194
Chicago					
	gas	0.467	0.120	0.406	0.993
	oil	0.054	0.056	0.090	0.200
	coal	--	0.006	0.306	0.312
	electric	0.074	0.246	0.155	0.475
	Total	0.595	0.428	0.957	1.980
Houston					
	gas	0.054	0.052	0.673	0.779
	oil	0.004	0.007	0.196	0.207
	coal	--	0.001	0.373	0.374
	electric	0.056	0.143	0.116	0.315
	Total	0.114	0.203	1.358	1.675

* 1EJ = 0.948 Quads = 0.948 x 10^{15} Btu

** Includes public sector consumption. The public sector accounts for from 14 to 23 percent of the sector total, depending on the AQCR and year. The commercial sector is comprised of SIC numbers 50 through 99.

***The industrial consumption total includes only the manufacturing SIC's (20 through 39). Excluded subsectors (mining, construction, and agriculture) account for approximately 12 percent of total industrial consumption (as a national average).

Note: Sector differences are a function of the relative size of the sector (e.g, the disparity between the disproportionately small size of Houston's residential and commercial sectors and the enormous size of Houston's industrial base). Energy use efficiencies within sectors are fairly constant across region and contribute only slightly to the variation indicated.

SOURCE: Resources for the Future. 1979. Energy in America's Future. Johns Hopkins University Press. Baltimore.

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TABLE 3. SOLAR MARKET DISAGGREGATION

Type of Structure	End Use	Fuel Type
Residential		
Single Family Detached	Hot water	Electricity
Single Family Attached	Space heat	Gas
Multifamily Low Rise	Space heating & cooling	Oil
Multifamily High Rise		
Mobile Home		
Commercial		
Office Building	Hot water	Electricity
Retail Wholesale	Space heat	Gas
School	Space heating & cooling	Oil
Warehouse		
Hospital		
Religious Service		
Auto Repair		
Hotel		
Miscellaneous		
Public		
Office	Hot water	Electricity
Hospital	Space heat	Gas
School	Space heating & cooling	Oil

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TABLE 3. (Continued)

Type of Structure	End Use	Fuel Type
Industrial	Boiler	
SIC* 20-25, 27 31, 36-39	Space heat	Electricity Gas Oil Coal
	Process water 49-100°C (120-212°F)	
	Process steam 100-316°C (212-600°F)	
	Process steam 316-816°C (600-1500°F)	
	Process heat	
	Less than 100°C (Less than 212°F)	Electricity Gas Oil Coal
	100-316°C (212-600°F)	
	316-816°C (600-1500°F)	

*The manufacturing SIC's analyzed are listed in Table 12, p. 40.

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the Oak Ridge National Laboratory (ORNL) Residential Energy Use Model,* provided growth trends to project the AQCR housing units for 1980, 1985, and 1995.

The census data yielded the number of housing units for each AQCR, disaggregated by housing type. In order to transform these numbers into energy consumption, the types and quantities of fuel used by each housing structure were determined. The loads for the five housing structures were based on EEA engineering calculations, load calculations (Hittman, 1979), and building energy consumption data. Table 4 provides an example of end-use loads for single family detached residences. The fuel types for water heating and space conditioning end uses were extracted from a regional cross-sectional matrix of home-heating fuel by type of structure.** The housing units, loads, and fuel type data supplied EEA with a matrix of market segments potentially displaceable by solar systems in the residential sector.

Commercial and Public Sectors

The commercial and public sectors were combined in constructing the data base for potential fuel displacement. The Oak Ridge National Laboratory (ORNL) Commercial Energy Use Simulation data provided a regional breakdown of all building types, fuel types, and end uses for historical (1970 to 1980) and projected (1980 to 2000) years. Table 5 shows an example of the Oak Ridge Regional data for three years: 1980, 1985, and 1995. Since each AQCR covers only a fraction of the region, the ORNL regional data was scaled down to the AQCR level (proportional scaling by population) to determine potential fuel displacement in the commercial sector.

The number of employees (based upon Commerce Department data) was used to represent the level of commercial activity within the AQCR, and comparing the number of AQCR to regional employees yields a ratio of AQCR energy consumption to regional energy consumption. This ratio, or AQCR percentage, was multiplied by the ORNL regional energy-use figures to determine AQCR energy consumption. A similar method was then used to check these figures. The Federal Energy Data Base (FEDS) for the commercial sector gives energy consumption by fuel type by State. Again using census data for employment, (U.S. Bureau of Census, 1979c; U.S. Bureau of Census, 1979b; and U.S. Bureau of Census, 1977), the percentage of the applicable States' total energy use by each AQCR was determined.

The AQCR energy use totals based on the regional percentage and the State percentage were relatively close (Table 6) indicating that the energy use/employee is approximately constant within each region. For the final AQCR 1980, 1985, and 1995 energy consumption, the State-based percentage was used on the assumption that State data estimate AQCR consumption more accurately than do regional data. These percentages, multiplied by the ORNL simulation data, give a complete picture of the potential solar mar-

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* Unpublished data from D.L. O'Neal, ORNL, May 1980.

**Personal communication with Jill King, Mathematical Policy Research, Inc., March 1980.

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TABLE 4. ENERGY CONSUMPTION IN SINGLE FAMILY DETACHED HOUSES

Units	Philadelphia	Chicago	Houston
Square meters per structure (Square feet)	130 (1400)	130 (1400)	130 (1400)
Total annual energy consumption, Gj/m² (therms/sq. ft)*	1.514 (1.333)	1.434 (1.263)	0.969 (0.853)
Annual end-use loads, Gj/m^2 (therms/sq. ft)			
Heating	0.897 (0.790)	0.943 (0.830)	0.242 (0.213)
Cooling	0.193 (0.170)	0.068 (0.060)	0.307 (0.270)
Water heating**	0.232 (0.204)	0.232 (0.204)	0.232 (0.204)
Lighting**	0.028 (0.025)	0.028 (0.025)	0.028 (0.025)
Cooking**	0.074 (0.065)	0.074 (0.065)	0.074 (0.065)
Other**	0.090 (0.079)	0.090 (0.079)	0.090 (0.079)

* One therm equals 100,000 Btu's.

**Okagaki, A., and Benson, J. County Energy Plan Guidebook, Institute for Ecological Policies, Fairfax, Virginia, 1977.

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TABLE 5. OAK RIDGE NATIONAL LABORATORY COMMERCIAL AND PUBLIC SECTOR ENERGY USE SIMULATION: OFFICE ENERGY USE REGION 6, INCLUDING HOUSTON AQCR

	EJ (Quads)*		
	1980	1985	1990
Space Heat			
Electric	0.0023 (0.0022)	0.0030 (0.0028)	0.0040 (0.0038)
Gas	0.0462 (0.0438)	0.0544 (0.0516)	0.0636 (0.0603)
Oil	0.0060 (0.0057)	0.0071 (0.0067)	0.0088 (0.0083)
Other	0.0025 (0.0024)	0.0024 (0.0023)	0.0022 (0.0021)
Cooling			
Electric	0.0694 (0.0658)	0.0823 (0.0778)	0.1012 (0.0959)
Gas	0.0011 (0.0010)	0.0004 (0.0004)	0.0
Oil	0.0	0.0	0.0
Other	0.0	0.0	0.0
Hot Water			
Electric	0.0002 (0.0002)	0.0002 (0.0002)	0.0003 (0.0003)
Gas	0.0011 (0.0010)	0.0012 (0.0011)	0.0014 (0.0013)
Oil	0.0002 (0.0002)	0.0002 (0.0002)	0.0002 (0.0002)
Other	0.0	0.0	0.0
Lighting			
Electric	0.0468 (0.0444)	0.0551 (0.0522)	0.0671 (0.0636)
Gas	0.0	0.0	0.0
Oil	0.0	0.0	0.0
Other	0.0	0.0	0.0
Other			
Electric	0.0117 (0.0111)	0.0146 (0.0138)	0.0172 (0.0163)
Gas	0.0	0.0	0.0
Oil	0.0	0.0	0.0
Other	0.0	0.0	0.0

*1 EJ = 0.948 x 10^{15} Btu

ket, including fuel type, end-use sector (commercial and public), and year. The aggregated potential solar market for each AQCR is shown in the third column of Table 6.

TABLE 6. TOTAL ACQR COMMERCIAL ENERGY USE, 1980

AQCR	Ratio Method 1 FED (by State)	Ratio Method 2 ORNL (by region)	AQCR/Region Energy Use EJ (Quads)*
Philadephia	0.2703	0.2455	0.1383 (0.1311)
Chicago	0.3470	0.3823	0.2885 (0.2735)
Houston	0.1319	0.1482	0.1820 (0.1725)

*1EJ = 0.948 x 10^{15} Btu = 0.948 Quads

In analyzing the solar market segments, the commercial and public sectors were separated in order to capture sectoral differences, primarily in financing schemes. The public vs. private sector differences extend to access to capital, required "rates of return," financial time horizon, and differences in tax applicability. Since the ORNL simulation gives data by building type, the private and public portions of the applicable building types (health, public buildings, and education) were separated by using private and public employment data. By comparing private and public hospital employees in each AQCR, for example, EEA determined the energy use attributable to private and public institutions.

Industrial Sector

The industrial market was first defined by fuel type and SIC industry categories using the Annual Survey of Manufacturers, 1976 (U.S. Bureau of Census, 1978b), along with EEA's Energy Consumption Data Base, as discussed in Data Sources and Methods for Industrial Energy Analysis (DOE, 1979). Similar to the commercial sector, employment data in each SIC manufacturing code (SIC 20-39) were used to scale down State energy consumption for each AQCR. The baseline data were projected to the reference years (1980, 1985, 1995) by translating the Bureau of Economic Analysis regional economic projections (BEA, 1977) into growth trends and breaking the subsequent totals into fuel types through EEA's Industrial Fuel Choice Model (IFCAM) (EEA, 1980). IFCAM projects fuel choice by assuming conservation effects, fuel price effects, and fuel availability.

The industrial sector was also disaggregated by end use, including boiler and process heat applications. The number of units in each AQCR by standard combustor class is available from the National Energy Data System

(NEDS) for the baseline year. These were projected for the three reference years by assuming that the same ratios between Btu consumption data and the number of units exist through time. As shown in Table 3, the industrial sector was ultimately disaggregated by boilers versus non-boilers (process heat), fuel type, and industry code.

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SECTION 5

TECHNICAL ASSESSMENT

INTRODUCTION

The overall objective of the technical assessment was to define systems for each end-use market segment and to assess performance factors affecting end-use solar energy utilization. The technical assessment was performed in four stages: 1) system screening, 2) system definition, 3) system performance, and 4) technical viability issues. In the system screening, analysis of solar technologies was limited to active solar thermal systems, due to their commercial readiness, their wide applicability to the market segments defined in Section 4, and the relatively straightforward analytic approach that could be used in their evaluation. In Step 2, prototypical active thermal systems were defined for each end use based on an analysis of solar system technology and end-use temperature requirements. Prototypical systems, in Step 3, were sized to determine the fraction of end-use energy the systems could provide. The sizing was based on analysis of system energy output and end-use load characteristics (magnitude, timing, etc.) affecting solar output utilization. Finally, in Step 4, it was determined that several industries were not favorable for solar market penetration, based on temperature requirements and magnitude of end-use energy demands. The potentially displaceable energy base in the industrial sector was narrowed to those industries most technically suited to solar energy systems.

TECHNICAL SCREENING

Solar energy is available in a wide range of forms (hydro, wind, radiation, etc.) and the number of solar technologies is large. Because of the limited time and resources for this study, a screening process was used to identify solar technologies with the following characteristics: 1) widely applicable to the subject market segments, 2) viable in the 1980 to 1995 timeframe, and 3) suitable to the simplified analysis proposed for this study. Based on these criteria, solar energy technologies were narrowed to active solar thermal systems.

Technical Applicability

Active solar thermal technologies can provide thermal energy to space heating and cooling and water heating end-uses. These end-uses encompass a majority of the total energy consumption in the commercial, residential, and public sectors. In the AQCR's studied, space heating and cooling and water heating energy consumption make up approximately 75 to 90 percent (depending

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on the year, structure type, and AQCR) of total energy consumption in the residential sector and an approximate average of 68 percent of total energy consumption in the commercial and public sectors. In the industrial sector, currently available solar thermal systems are potentially applicable to a substantial fraction of industrial process needs. According to a study by Intertechnology Corporation (Frazer, 1977), at least 28 percent of industrial process heat is at temperatures below 288°C (550°F), which is technically possible with parabolic trough solar collectors. Half of all industrial process heat requirements are for end-use temperatures below 593°C (1100°F), attainable with point focusing parabolic dish collectors (which are just becoming commercially available).

Commercial Viability

In addition to potentially broad technical applicability, solar thermal technologies have the capability for significant market penetration in the 1980 to 1995 timeframe. All of the collector types evaluated in this study are currently being manufactured, although operating systems do not exist for many industrial applications. Solar thermal equipment manufacturing industries, distribution networks, and installation and service businesses currently exist in each of the AQCR's under review in this study (for residential and commercial systems).

Level of Analysis

The analysis of solar thermal technologies is relatively straightforward. The marginal utility of evaluating several other technologies was not considered justified, because the technologies were difficult to analyze and had a smaller market applicability and/or were less advanced in their development than solar thermal technologies. They include:

- Photovoltaic systems. Photovoltaic systems were analyzed only briefly. A detailed review of photovoltaics was not considered due to the high costs of these systems (relative to thermal systems), the relatively small market share accounted for by strictly electric end uses (lighting, stationary motor drive, etc.), and the complexity of properly evaluating photovoltaic systems (given questions of private vs. utility ownership, future electric rate structures, the wide variability of electric load profiles among end users, etc.). Likewise, wind systems and central station electric generation (whether thermal, photovoltaic, or wind) were not considered.

- Passive solar energy systems. These were not evaluated because of the difficulty in identifying and characterizing passive applications over all building types in all the sectors (given questions on the orientation of buildings, retrofitability, costs, performance, etc.).

This study focused on technologies that appear to have the largest fuel displacement potential during the 1980-1995 timeframe. Technological breakthroughs and/or changing market conditions may increase the penetration of the solar options which were excluded from this study. Further study is required to properly evaluate the fuel displacement potential of these excluded technologies.

SYSTEM DEFINITION

Overview

Defining prototypical systems involved 1) assessing collector technology and matching collector types to end-use temperature profiles and 2) defining collector/end use matches in the context of overall systems, including auxiliary system equipment specific to the given end use (e.g., absorption chillers for cooling systems). Four collector types were evaluated: (1) flat plate collectors, (2) compound parabolic concentrators,* (3) parabolic troughs, and (4) parabolic dishes. The end-uses considered were space heating and cooling and water heating for the commercial, residential, and public sectors. Industrial sector end-uses considered are space heating and process heater and boilers demand (at temperatures below 816°C (1500°F)).

Commercial, Residential, Public Sectors

Solar thermal systems utilized for water heating and space heating and cooling end uses are composed of four main components (and a number of smaller components, pumps, controls, expansion tanks, etc.): 1) the collector, 2) the thermal storage tank (and its heat exchanger), 3) a storage-end use heat exchanger to transfer heat from storage fluid to the end use working fluid, and 4) auxiliary backup subsystem.

Collector Subsystem -- Table 7 lists the collector end-use match for each of the sectors as well as collector operating temperature used in this analysis. Collectors include flat plate (FP) and compound parabolic concentrator (CPC) collectors. Flat plate collectors have an operating temperature range of 38°C (100°F) to 93°C (200°F). Compound parabolic concentrator collectors operate at between 82°C (180°F) and 204°C (400°F).

The hot water temperature requirements of all the building types studied in these three sectors fall between 49°C (120°F) and 71°C (160°F) (Farahan, 1977). A solar thermal system based on flat plate collectors operating at 60°C (140°F) was used for the performance evaluation of all solar hot water end-use applications.

For heating and cooling systems, flat plate collectors operating at 85°C (185°F) were matched to residential space heating and cooling end uses and CPC collectors operating at 99°C (210°F) were matched to commercial and public space heating and cooling end uses. Space cooling temperature requirements were used to select the collector type and its operating temperature.

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*Incorporates a twin trough concentrator, a design which has the advantage of being less sensitive to sun attitude than most system designs and frequently is deployed without a tracking system.

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TABLE 7. END USE-COLLECTOR TYPE MATCH, RESIDENTIAL AND COMMERCIAL/PUBLIC SECTORS

Sector	End Use	End-Use Temperature Requirements	Matched Collector Type	Collector Operating Temperatures*
Residential	Water Heating	49-71°C (120-160°F)**	Flat Plate	60°C (140°F)
	Space Heating	>66°C (>150°F)	Flat Plate	85°C (185°F)
	Space Cooling	77-96°C (170-205°F)***	Flat Plate	85°C (185°F)
Commercial, Public	Water Heating	49-71°C (120-160°F)**	Flat Plate	60°C (140°F)
	Space Heating	>82°C (>180°F)§	CPC	99°C (210°F)
	Space Cooling	93-115°C (200-240°F)#	CPC	99°C (210°F)

* Temperature used for collector-load performance analysis. Lower collector operating temperature can be utilized by end uses in preheat applications. For this reason, collector-load performance may be on the conservative side.

** E. Farahan. *Residential Electric and Gas Water Heaters*. Argonne National Laboratories, ANL/CES/TE77-2. 1977

***At the time of this study, only Arkla Industries, Inc. produced a residential absorption chiller unit. Its suggested operating temperature range is 77°C (170°F) to 96°C (205°F). Some major Japanese firms are now investigating this technology.

§ F.S. Durbin. Solar Energy Design for Existing Buildings. *ASHRAE Journal*. November 1975.

# Commercial absorption chiller temperature requirements. Personal communication with J. Winborne, Trane Corporation. June 14, 1980.

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Absorption chillers were considered the best commercially available technology for solar cooling in the 1980-2000 time frame. Solar assisted space cooling (absorption chiller) temperature requirements are greater than those for space heating for all the building types studied: 77°C (170°F) vs. 66°C (150°F), respectively, for the residential sector, and 93°C (200°F) vs. 82°C (180°F), respectively, for the commercial and public sectors.

Storage Subsystem -- Short-term thermal storage (two to three days) was considered necessary to supply thermal energy during poor weather conditions or to store thermal energy during periods of light end-use loads. Economic studies have shown that optimum storage capacity is about 51.1 to 102 liters/m^2 (1.25 to 2.5 gallons/ft^2) of collector area (Lof, 1973). As long as the ratio is greater than 51.1 liters per square meter of collector, storage capacity is not a critical design parameter (Beckman, 1977) for short-term storage. In this analysis, a storage capacity of 80 liters/m^2 (2 gallons/ft^2) of collector was used.

Heat Exchange Subsystem -- In hydronic space heating, absorption cooling, and water heating end-use applications, a liquid-to-liquid heat exchanger is used to transfer heat from storage liquid to end-use working fluid. Forced air heating systems will utilize a liquid-to-air heat exchanger to transfer thermal energy from storage liquid to heat distribution air. It was assumed that storage end-use heat exchangers could be retrofitted to all existing water heating and space heating and cooling (hydronic and central air) systems.

Backup Subsystem -- Solar thermal systems were considered in this analysis to be supplemental energy sources because of consistent load requirements and potentially wide variation in weather. Thus in solar system performance, auxiliary capacity (conventional energy sources such as gas furnace, electric water heating, etc.) was required to meet 100 percent of load requirements.

Industrial System Definition

Industrial end uses span a range of process types, energy delivery modes (preheat vs. process heat), and temperature ranges. Processes may involve boilers or nonboilers. Nonboilers (process heaters) encompass many types: tubestill heaters, reverberatory furnaces, kilns, etc. The range of industrial end use temperatures varies from 49°C (120°F) process water to around 1650°C (3000°F) process heat temperatures. Technical attributes of solar industrial process heat systems limit solar system applications.

Solar applications for industrial boilers typically occur in two forms: either as heat exchangers or flash steam generators. Heat exchanger units are commonly used in industry for indirect heating and vary in capacity from 2 GJ/hr to 250 GJ/hr (about 250 MMBtu/hr.) Conventional fossil-fired boilers cannot be retrofitted to solar boilers in the way that some oil burners can be retrofitted to coal use. Thus, a solar system can be installed as a new boiler or retrofitted in an indirect heat or preheat mode. Figures 4 and 5 illustrate these two cases.

FIGURE 4
SOLAR SYSTEM TO PROVIDE PROCESS STEAM

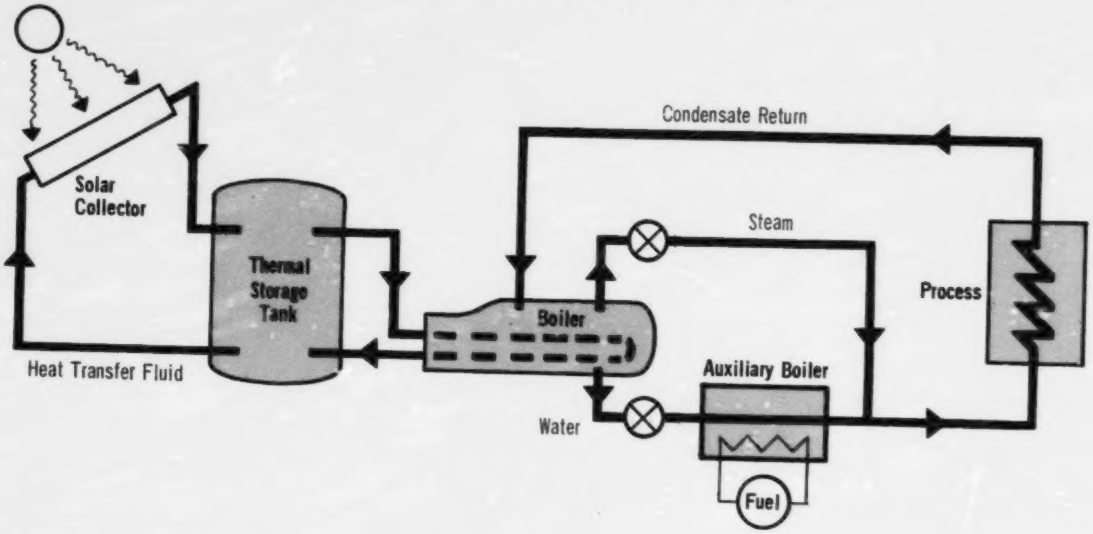
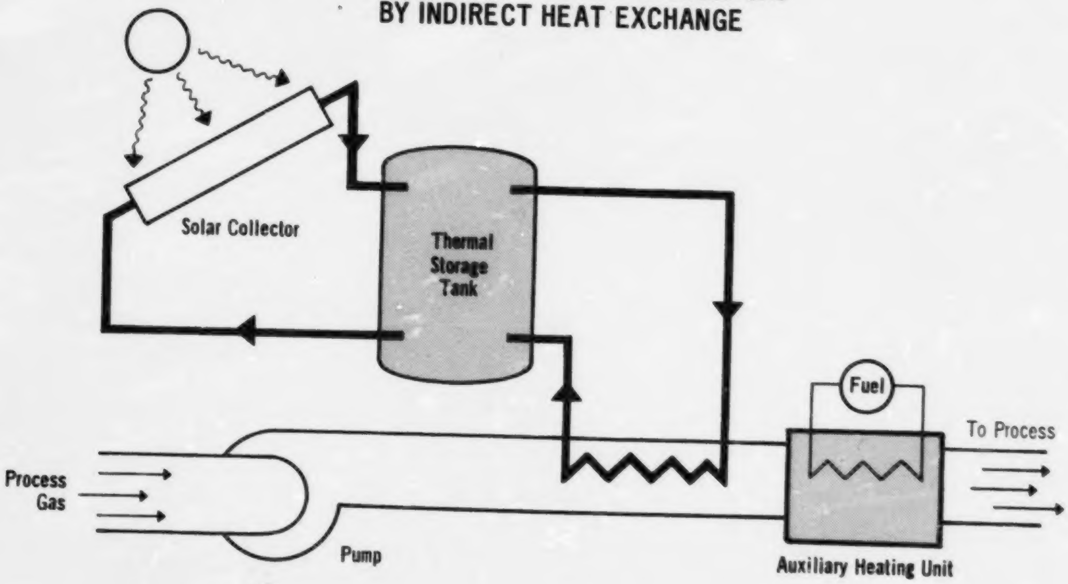

Solar Collector
Thermal Storage Tank
Heat Transfer Fluid
Condensate Return
Steam
Process
Boiler
Auxiliary Boiler
Water
Fuel

FIGURE 5
SOLAR SYSTEM TO HEAT PROCESS GAS BY INDIRECT HEAT EXCHANGE


Solar Collector
Thermal Storage Tank
Fuel
To Process
Process Gas
Pump
Auxiliary Heating Unit

Source: Draft Programmatic Enviromental Assessment for DOE's Solar Agricultural and Industrial Process Heat Program, 1979.

The primary cost factors in defining industrial systems are 1) process temperature and 2) boilers vs. heater application. Prototypical systems were subdivided into three temperature categories which paralleled the temperature capabilities of the different collector types: less than 93°C (200°F) for flat plates; 93-316°C (200-600°F) for CPC and parabolic troughs; and 316-816°C (600-1500°F) for parabolic dishes (see Table 8).

Prototypical systems were also divided into boiler and process heater applications. Process heaters require indirect heat systems (whether new or retrofit) while boiler applications may, as mentioned, either be indirect heat retrofits or new boilers. While installed costs of all these applications are considered to be the same for purposes of this analysis (see Section 6), efficiencies (which affect solar costs and fuel displacement) are different for heaters and boilers. The distinction therefore was made between boilers and process heaters.

No storage capability was included for industrial systems. The high reliability requirements of industrial users will necessitate full conventional backup capacity. It is expected that most near-term solar industrial process heat systems will not include storage and will act as fuel savers by supplementing conventional systems (Brown et al., 1980). This analysis assumed that industrial processes can absorb 100 percent of the peak output of the collectors. Considerable detail on the dynamic behavior of the solar system and the process would be needed to analyze industrial systems that include storage.

SYSTEM PERFORMANCE AND SIZING

Introduction

The ultimate value and cost of a solar energy system hinges critically on the output of the system and the efficiency with which it is used. This is both a function of the system and of performance and end-use load characteristics. Solar systems rarely can economically meet total end-use energy requirements because of the mismatch between the magnitude and timing (diurnally, seasonally) of solar output and end-use load sizes and temporal profiles. The degree of match (both in design and real time use) between solar output and end-use loads is important because it defines the upward limit on solar fuel displacement capability and is a major factor in determining the costs of the system.*

Solar systems were sized to individual end-uses for the residential, commercial, and public sectors to maximize the efficiency of solar output utilization.** For industrial systems, sizing was based on an analysis of the land requirements associated with meeting the energy output of typical

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* For a fixed system cost, the higher the efficiency of using collector output, the lower the solar cost on a $/GJ basis.

**A system sized to meet 100 percent of peak demand is not an economic system because much of the system goes unused at off-peak periods.

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TABLE 8. END USE-COLLECTOR TYPE MATCH, INDUSTRIAL SECTOR

Sector	End Use	End Use Temperature Requirements	Matched Collector Type	Collector Operating Temperatures*
Industry	Space Heating	>66°C (>150°F)	Flat Plate	85°C (185°F)
	Hot Water, Process	40-66°C (120-150°F)	Flat Plate	60°C, 85°C (140°F,185°F)
	Heater, Boiler	93-204°C (200°F-400°F)	CPC	99°C, 150°C (210°F,300°F)
		150-316°C (300°F-600°F)	Parabolic Trough	150°C, 232°C (300°F,450°F)
		316-816°C (600°F-1500°F)**	Parabolic Dish	316°C, 650°C (600°F,1200°F)

* Temperature used for collector-load performance analysis. Lower collector operating temperature can be utilized by end uses in preheat applications. For this reason collector-load performance may be on the conservative side.

**Two axis tracking parabolic dish collectors have attained temperatures of up to 2500°C (4500°F) at their point focus, however it is inefficient and costly to transfer working fluid at temperatures above 816°C (1500°F) from the point source to the industrial end use. Personal communication with V. Truscello, Jet Propulsion Laboratory, July 16, 1980; S.A. Stadjuhor, Feasibility Evaluation for Solar Industrial Process Heat Applications. SERI, 1980.

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industrial boilers and process heaters. For all sectors, system sizing involved an analysis of the interrelationship of two factors: system output and end-use load demands. This section is divided into three parts discussing each of the relevant variables: solar output, end-use loads, and system sizing and performance.

System Output

The energy output of a solar system is a function of the performance of the system's collectors and auxiliary subsystems (heat exchangers, thermal storage, etc). Subsystem performance was calculated by assuming values for system heat exchanger efficiencies, thermal line losses, storage losses, and the like. Line losses, heat lost to the ambient air in transporting collector fluid to storage, etc. were assumed to be 8 percent of the collector thermal output (Brink, 1980) for all applications.

Collector output was calculated for each of the four collector types employed for each AQCR. Collector output was then adjusted to reflect the system efficiency to determine the output of the total system.

Collector performance is usually specified in terms of an instantaneous or peak efficiency under ideal operating conditions (clear sky and normal sun-collector incidence conditions.) Actual solar units rarely witness perfect operating conditions. For this reason, long-term collector energy deliveries typical of local weather conditions and sun-collector incidence angles must be estimated.

A recently developed procedure (Pereira and Rabl, 1979) was used to calculate long-term collector performance. The Pereira-Rabl model offers the advantage of automatically averaging year-to-year weather fluctuations and is sufficiently simple to permit hand calculation. In a comparison with an hour-to-hour computer simulation utilizing exhaustive weather data (only available for five sites in the United States), the Pereira-Rabl model does not show any significant bias with respect to location or times of year. Uncertainty in the long-term Pereira-Rabl collector performance model was found to be on the order of 5 percent with error tending toward the conservative side (i.e., underpredicted performance). Using the Pereira- Rabl model, long-term collector performance was calculated on a per square meter basis for each of the three AQCR's for four thermal collector types, each operating at two different fluid output temperatures (see Figure 6). The four thermal collector types analyzed include double glazed* flat plate collectors operating at 60°C (140°F) and 85°C (185°F), fixed compound parabolic concentrator (CPC) collectors with evacuated receiver operating at 100°C (210°F) and 150°C (300°F), one axis tracking concentrator collector operating at 150°C (300°F) and 232°C (450°F), and one two-axis tracking parabolic dish collector operating at 316°C (600°F) and 650°C (1200°F).

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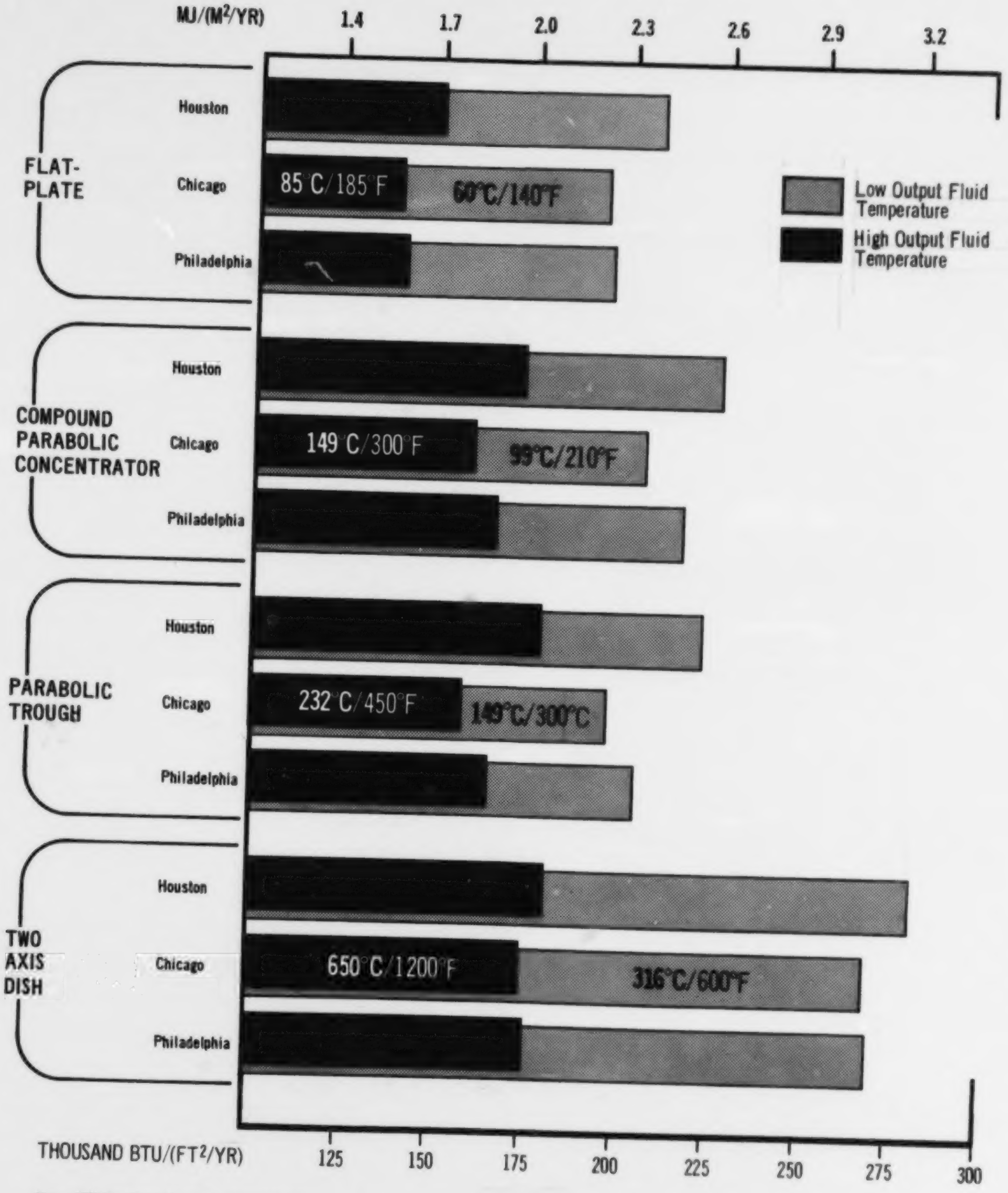
*The double (vs. single) glazed assumption is not likely to have a significant impact on the analysis. While costs drop from shifting from double to single glazed systems, collector performance also declines. The cost per unit of output does not change much.

FIGURE 6

LONG-TERM AVERAGE ENERGY OUTPUT BY COLLECTOR TYPE, TEMPERATURE, AND AQCR



Note: 1000 Btu/(Ft²/Yr) equals 87.7 MJ/(M²/Yr)

The parameters used in calculating the performance of each of the thermal collector types are representative of currently available technology and are listed in Table 9.

Collector orientation in all fixed collector cases was due south. The collector tilt from a horizontal surface in all fixed thermal collector cases (flat plate, CPC) was assumed to be approximately equal to the latitude of the appropriate AQCR plus 5 to 15 degrees, depending on end use and the AQCR being analyzed. Latitude plus 15 degrees was used as the collector tilt angle in thermal applications having their highest building loads in winter. Collector tilt angle of latitude plus 5 degrees was used in Houston space heating and cooling applications as a compromise between the low insolation and heating load of winter and the high insolation and cooling load of summer.

Figure 6 indicates the calculated collector output of flat plates, compound parabolic concentrators, compound parabolic troughs, and two-axis dishes. Collector output varies between the AQCR's, but not as significantly as might be expected. The output decline occurring at higher temperature operations (due to lower efficiency of collectors) was larger than regional variation in energy output. The output of a CPC in Houston operating at 210°F is 9 percent and 4 percent higher than the output of CPC's operating at the same temperature in Chicago and Philadelphia, respectively. The output of a CPC at 210°F in Houston, however, was 18 percent higher than the CPC output from the same system operating at 300°F. The similarity in collector output between Houston and the other AQCR's is a function of several factors, including high relative humidity levels in Houston. Humidity reduces total insolation levels and diffuses direct radiation, which impedes the performance of concentration collectors in particular.

End-Use Loads

The overall solar system efficiency and the fraction of the load supplied by solar energy depend on the relationship between the output of the system and end-use loads.

Residential, Commercial, and Public Sectors -- End-uses analyzed for these sectors consist of hot water heating, space heating, and space cooling. The end-use loads for prototypical structures were used to size solar systems and to project sector energy demand. The prototypical commercial structures are office buildings, retail/wholesale buildings, and schools. The public sector included office buildings and schools. In the residential sector, the prototypical units were single-family detached, single- family attached, and multifamily high rise. Loads for the prototypic structures for 1980 were based on a number of different sources, including building audits in the AQCR studies, EEA engineering calculations, and building energy consumption models (Hittman, 1976; Intertechnology, 1976; AIA, 1978; TRW, 1974). The calculated loads reflect regional climatic variations (e.g., Houston heating loads are small, and cooling loads are large).

TABLE 9. PERFORMANCE PARAMETERS USED IN THE CALCULATION OF LONG-TERM COLLECTOR PERFORMANCE

	Collector Type			
	Flat Plate*	CPC**	Parabolic Trough***	Parabolic Dish§
Efficiency	0.75	0.60	0.65	0.65
Heat Loss Coefficient:				
KJ/hour meter^2°C	14.0	2.9	2.5	0.72
Btu/hour ft^2°F	(0.70)	(0.14)	(0.12)	(0.035)
Heat Extraction Efficiency Factor	0.90	0.90	0.95	0.90
Concentration Ratio	1.0	1.5	20.0	500.0
Acceptance Angle	NA	68°	NA	NA

* Double glazed collector with selective coating.

** Fixed CPC with evacuated receiver.

***Parabolic trough with non-evacuated selective receivers.

§ Two-axis concentrating parabolic dish collectors are just becoming commercially available and few test data are available on collectors at the present time. These values were estimated.

NA = Not Applicable.

Annual end-use loads were projected from 1980 to 1985 and 1995 based on estimated effects of conservation induced by fuel prices and local building codes (ASHRAE 90-75) (Arthur D. Little, 1976). Conservation measures included changes in: appliance efficiencies (Table 10), the thermal performance of the building envelope, and consumer behavior (e.g., lowering thermostats).

The project team also compared projected monthly hot water, space heating, and space cooling demands to solar output. Space heating and cooling loads were allocated on a monthly basis based upon the heating and cooling degree days. Hot water heating loads show less pronounced monthly variation than do heating and cooling loads, but the analysis in this report does reflect variations in city water temperatures.

Loads in the Industrial Sector -- Industrial loads differ from loads in the other sectors in several ways.

First, industrial sector loads may be extremely large, as measured in GJ per hour. Large amounts of land for collector sitings are needed to meet only a small portion of the load. In the residential, commercial, and public sectors, loads are generally small enough that available roof areas can site collectors, with few exceptions,* to meet a substantial load fraction (10 percent or more).

Second, industrial loads are more variable than loads in the other sectors. Wide ranges characterize the two parameters that determine industrial loads: 1) boiler (or process heater) size and 2) capacity utilization rates. Process heaters and boiler sizes may vary from 5 GJ/hr to as large as 500 GJ/hr (or from about 5 MMBtu/hr to 500 MMBtu/hr). Capacity utilization rates may vary from 0.10 to 0.90. The energy output of a boiler equals its capacity rating times its capacity utilization rate; thus, the range of typical boiler and process heater demands is substantial. There are some industry-specific generalizations about load demands that can be made. Some industries are characterized by small boilers and process heaters and low capacity utilization rates (hence, relatively small energy demand or loads), whereas other industries are characterized by large boiler/process heaters with high firing rates (hence, large loads). Industries in the former category include food, textiles, tobacco, wood fixtures, and miscellaneous manufactures. Industries in the latter categories include all the major energy consuming SIC's with the exception of food and textiles (e.g., Organic Chemicals, Petroleum Refining, Stone, Clay, and Glass, etc.).

Third, while industrial loads vary considerably between industries, process and boiler energy demand tends to show less pronounced regional and seasonal perturbations than loads for the residential, commercial, and public sectors. There are seasonal fluctuations in some industries (e.g.,

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*Multi-family high rise buildings are one exception. These buildings have a small roof area to floor space ratio; not enough roof space exists to meet both hot water demands and space heating and cooling requirements.

TABLE 10. RESIDENTIAL AND COMMERCIAL EQUIPMENT EFFICIENCIES

	1980	1985	1995
Residential			
Space Conditioning			
Solar Cooling*	0.5	0.6	0.7
Air Conditioning**	7.0	7.3	8.0
Gas Heat	0.6	0.66	0.7
Oil Heat	0.55	0.56	0.6
Electric Heat	0.95	0.95	0.95
Water Heating			
Gas	0.64	0.66	0.7
Oil	0.50	0.50	0.55
Electric	0.95	0.95	0.97
Commercial/Government			
Space Conditioning			
Solar Cooling*	0.5	0.6	0.7
Air Conditioning**	7.5	7.9	8.5
Gas Heat	0.7	0.74	0.8
Oil Heat	0.62	0.66	0.7
Electric Heat	0.95	0.95	0.97
Water Heating			
Gas	0.64	0.66	0.7
Oil	0.5	0.5	0.55
Electric	0.95	0.95	0.97

* Absorption cycle cooling.

**Refrigeration cycle cooling.

food canning), but in many others loads are relatively constant. The lack of seasonality made it unnecessary to determine industrial loads on a monthly basis.

Fourth, there often is more flexibility in meeting industrial loads than loads in the other sectors. Once a hot water load is specified for a commercial building, for example, the range of equipment options to meet it is relatively limited. In industry, on the other hand, a specified load can be met in a number of ways: by several boilers or one large boiler, by direct heat or indirect heat, with waste heat or process steam. Loads for different plants within a given industry may vary depending on the size of the plant and the way in which process units are integrated. These factors complicate a generic analysis.

Industrial loads were determined generically for each of the manufacturing SIC's as a weighted average based upon the relative number of boilers and process heaters for each SIC and their sizes and capacity utilization rates. Information was extracted from the background documentation of DOE's Industrial Sector Technology Use Model (DOE, 1979a). A conservation effect was assumed to affect consumption in 1985 and 1995. That is, the model competes new and existing heating and cooling technologies and conservation technologies to predict technology inventories specified by size, fuel type and SIC. This approach was used to determine the number and characteristics of industry combustors for this study.

SYSTEM SIZING

Residential, Commercial, and Public Sectors

Solar system sizing is necessary to estimate solar performance on a $/GJ basis and to assess fuel displacement potential. As noted before, the sizing analysis was based on an evaluation of three commercial buildings (office buildings, retail/wholesale, and schools), two public buildings (office buildings and schools), and three residential buildings (single family detached, single family attached, and multifamily high rise).* The results of the sizing analysis reflect the relationship between solar system output utilization and end-use load profile characteristics. Defined parameters of the buildings included building size and roof area and monthly end-use loads and fuel mix, as noted.

The fraction of end-use load requirements provided by solar energy systems was determined for three system sizes. The maximum system size was based upon the roof area of each prototypic building. The three system sizes spanned a load fraction range of from 30 to 80 percent for hot water and 10 to 60 percent for space heating and cooling (on an annual basis). The system selected for calculating fuel displacement potential was based on the size that most closely approximated the economic optimum, i.e., the system size most efficiently utilized on a $/Gj basis. The estimated optimum size typically fell in the 10 to 20 percent range for space heating and cooling and in the 40 to 60 percent range for hot water heating, for all building types and regions. These results correspond to those of other optimization studies (ADL, 1978).

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*These buildings account for a large share of total sector energy consumption; for example, 65 percent, 88 percent, and 73 percent of the 1980 commercial, public, and residential energy consumption, respectively, for Houston.

The methodology employed to calculate solar system utilization for the three system sizes involved a comparison of the monthly end-use load demand and monthly solar system output. The smaller quantity is assumed to be the amount of energy displaced by the solar system. That is, if the load requirement is less than the supply, the load (the amount of supply utilized) is credited; if, on the other hand, the load requirement (for a given month) is greater than the supply, only the supply is credited to displaced energy. By aggregating the displaced energy for each month over a year, total annual solar system load performance was calculated.

This approach assumes that thermal storage will absorb all the fluctuations in collector output and end-use demand. The 80 liters per square meter (2 gallons/ft^2) of collector area will absorb hour-to-hour and day-to-day output or consumption fluctuations but the storage does not have enough capacity to outlast adverse conditions for more than two to three days. This assumption would overestimate solar system load performance by less than 10 percent.

Industrial System Sizing

This study assumed that industrial process loads would always be greater than the thermal output of the collector and that no thermal storage would be utilized. Thus, the solar system operates as a supplemental energy source, fully utilized except during boiler and process heater downtime. The end use loads in industry, in fact, are so much larger than solar system output in many cases that the solar end-use load fraction may represent an insignificant load fraction. This is not only a result of the magnitude of industrial demand but also of technical and land constraints that limit solar systems sizes and output.

The land required to generate 5 GJ/hr (5 MMBtu/hr) varies between 1.56 and 2.5 hectares* (3.85 and 6.2 acres) for parabolic trough systems, depending on the AQCR and the temperature of system operation (see Table 11). It was assumed, for this reason, that solar industrial systems would be limited to providing 5 GJ (5 MMBtu/hr) or less, regardless of the end use application. The restriction of solar system size to 5 GJ/hr (5 MMBtu/ hr) or less is consistent with the system size ranges currently being demonstrated by DOE's Industrial Process Program and is reasonable, given

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* 1 hectare = 10,000 square meters.

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TABLE 11. LAND REQUIREMENTS FOR A 5 GJ/HR (MMBTU/HR) PARABOLIC TROUGH SYSTEM*

Temperature of Collector Operation	Required Hectares** (Acres) of Land		
	Philadelphia	AQCR Chicago	Houston
150°C (300°F)	1.90 (4.70)	1.78 (4.40)	1.56 (3.85)
232°C (450°F)	2.39 (5.90)	2.51 (6.20)	2.23 (5.50)

* Based on calculated system output, a capacity utilization factor of 0.20, and 6.6m (20 ft) spacing between collector rows. The assumption of 6.6m (20 ft) spacing is commonly made, but simplifies the comparison in a way that possibly underestimates the land required in Philadelphia and Chicago by a small amount relative to the land required for Houston. This is because collectors in Houston can be situated closer without shading each other than collectors in Philadelphia and Chicago. Spacing is required both to avoid excessive shading and to allow maintenance personnel access through the field.

**1 hectare = 10,000 square meters.

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industrial land costs.* The two operating DOE industrial process steam demonstrations operate at approximately 1 GJ/hr (1 MMBtu/hr). All of the new industrial solar demonstrations budgeted or under construction (there are three) will provide around 1 GJ/hr (1 MMBtu/hr). Three more industrial solar demonstrations (not yet budgeted) will produce somewhat over 4 GJ/hr (4 MMBtu/hr).**

The capacity utilization rate of solar systems was assumed to be 0.21, equivalent to using solar output seven hours per day, five days per week. The assumption of a 0.21 capacity factor will underestimate solar utilization for industries that operate six or seven days per week. (The capacity utilization rate in these cases would increase to as high as 0.29.) On the other hand, the 21 percent capacity factor overestimates the solar contribution for plants that are highly seasonal in nature (such as canning plants in the food industry).

Solar load fractions were calculated based on the 5 GJ/hr (MMBtu/hr) solar system size limitation and a 0.21 capacity factor. Load fractions for large boiler, energy-intensive SIC's such as Organic Chemicals (SIC 28), Petroleum Refining (SIC 29), and Paper (SIC 26) were found to be on the order of one percent or less. Load fractions for smaller boiler, process heater industries such as food, textiles, wood, printing, miscellaneous manufacturing, etc. varied from 8 to 12 percent.

TECHNICAL VIABILITY

The potentially displaceable fuel base in the industrial sector was narrowed to 12 SIC's based on the lower process temperature ranges and the greater potential for solar to displace a significant percentage of fuel consumption in the small boiler and process heater industries (See Table 12). These 12 SIC's account for 13.7, 14.9 and 0.1 percent of the total non-electrical industrial projected energy consumption in the Philadelphia, Chicago, and Houston AQCR's, respectively, in 1985. The estimated aggregate solar load fraction calculated for these 12 SIC's is 12, 10, and 8 percent of their total non-electrical energy consumption for Philadelphia, Chicago, and Houston, respectively. The difference in solar load fractions between AQCR's reflects the variation in industry size and capacity utilization rates among the individual SIC's. That is, the distribution and population of SIC types within an AQCR affect the aggregate solar load factor (and thus fuel displacement).

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* Industrial land costs (1980 dollars) may vary from $49,000 to $321,000 per hectare ($20,000 to $130,000 dollars per acre) (Whisnant, 1979). Land costs were not considered in the evaluation of solar industrial economics (Section 4), due to the difficulty of estimating generic land availability in industry. Thus, the limitation to 5 GJ/hr may be optimistic, if available roof area or inexpensive land is not available for collector siting.

**Personal communication with Ken Bergeron, Sandia Laboratories.

TABLE 12. MANUFACTURING SIC's ANALYZED FOR SOLAR SYSTEMS APPLICATIONS IN THE INDUSTRIAL SECTOR

SIC	Manufacturing Industry
20	Food and Kindred Products
21	Tobacco Manufacture
22	Textile Mill Products
23	Apparel and Other Textiles
24	Lumber and Wood Products
25	Furniture and Fixtures
27	Printing and Publishing
31	Leather Products
36	Electric and Electronic Equipment
37	Transportation Equipment
38	Instruments and Related Products
39	Miscellaneous Manufacturing

The limitation of the analysis of 12 SIC's is consistent with DOE's demonstration program. With the exception of concrete block curing applications in the Stone, Clay, and Glass industry, all of DOE's demonstrations in the manufacturing SIC's are in industries considered in this analysis. Further research is needed to identify and quantify the fuel displacement potential of all isolated case-specific applications, which were judged beyond the scope of this study. The small solar load fractions calculated for the excluded SIC's indicate that their omission from the analysis should not significantly affect results.

SECTION 6

ECONOMICS

INTRODUCTION

In this study, the annualized life cycle costs of solar energy systems (in dollars per GJ) were derived under a base case for each viable end use. The annualized solar cost then was compared with the levelized price of fossil fuels. A "relative attractiveness ratio" (RAR), the ratio of levelized price of fossil fuel displaced to annualized solar cost, was calculated for each market segment. When the RAR of a given end use and fuel exceeded 1.0, the solar system was considered competitive in that market segment. The end-use-by-fuel matrix leads to a base case with 1,467 market segments for which RAR's were generated. This economic analysis provided the foundation for calculating market penetration, fuel displacement, and emissions impacts.

RAR ASSUMPTIONS

The computation of RAR's was predicated on two key assumptions: 1) a full capacity fossil-fired backup would be required for all solar systems, and 2) maintenance and operating expenses of running the backup units of the solar system would be the same as the maintenance and operating costs for the conventional system (with the exception of fuel costs). In short, it was assumed that the principal impact of the solar system is to reduce the fossil fuel burned by the conventional system. This allows the direct comparison of solar system costs with fuel cost without regard to the cost of the conventional system.

As noted, the relative attractiveness ratio is expressed in terms of the displaced fuel type for a given end use. The fuel bill savings accruing from the operation of the solar system are a function of the fuel displaced, rather than the solar energy provided. Fuel displacement will vary depending on the efficiency of the conventional backup unit and is calculated by multiplying the solar energy provided to the end use by the reciprocal of the conventional unit conversion efficiency.* Thus, although relative attractiveness ratios are calculated without regard to conventional unit costs, the efficiency of conventional units is embodied in the ratios as we have defined them.

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*For example, oil saved in solar hot water heat applications per unit of energy of solar input equals 1.8 (assumes 0.55 conversion efficiency, for a 1980 oil water heater). If the solar system cost and fuel cost are identical on a $/GJ basis, the relative attractiveness ratio incorporating the conventional unit conversion efficiency would be 1.8/1 in this case.

The cancellation of conventional system costs (by assuming identical conventional and backup systems and identical non-fuel operating expenses) is a simplification that often is made in generic (non-site-specific) solar energy cost studies (Dickenson and Freeman, 1977; Dickenson and Brown, 1979; Brown et al., 1979; Clark, 1976). Two basic advantages of this approach are 1) avoiding the need to cost out a conventional system and 2) allowing a direct comparison of the two key variables that will determine the economic viability of solar energy (solar system costs and fuel displacement benefits).

ANNUALIZED SYSTEM COSTS

Annualized system costs are a function of two factors: 1) initial installed system costs and 2) system financing assumptions (tax credits, depreciation, tax status, etc.). The next two sections discuss each of these factors in turn.

Installed System Costs

Determining reasonable installed solar costs is difficult on a generic level. Due to limited operating experience, installed system costs must be typically estimated or generalized from solar demonstrations. In other studies, procedures for estimating installation costs in the industrial sector (based on "factor estimating") have been employed, but considerable additional effort is required to refine this methodology for solar system cost estimation (Brown et al., 1979). Generalizing costs from demonstrations requires estimation of the degree to which demonstration equipment costs and installation procedures will reflect those of commercial solar systems. However, many solar systems (e.g., process heat or steam systems above 316°C) have not yet been demonstrated or have not undergone even lab tests (DOE, 1980b), so cost estimates are based upon very limited data.

Another factor complicating solar cost estimation (on a generic level) is the variation encountered in unit equipment costs. In a 1977 cost survey of 24 commercial solar demonstrations (King et al., 1979), unit collector costs were found to vary between \$108/sq meter and \$1,760/sq meter (\$10/sq ft and \$163/sq ft); support structures between \$26/sq meter and \$280/sq. meter (\$2.40/sq ft and \$26/sq ft); and piping and insulation costs between \$34.60/sq meter and \$345/sq meter (\$3.20/sq ft and \$32/sq ft). Some of the variability is a function of factors that can be accounted for in a generic level study. For example, collector costs at the lower end of the range were

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[1] Thus, the solar system would be more economic than burning fossil fuel. If the conversion efficiency was not included, the RAR would equal 1, by definition, indicating that the two alternatives are equally competitive. The ratio 1.8/1 is the relevant one for making the cost comparison in this example.

for flat plate collectors, whereas costs at the upper end of the range reflect tubular or concentrating liquid collectors. However, site-specific factors cannot be readily addressed on a generic level. For example, variation in pipe work and insulation costs is partially a function of the use of union labor, union wage rates, and local building codes and ordinances*. These factors make it difficult to determine representative solar system installed costs.**

The average installed solar costs used in the baseline analysis are indicated in Table 13. The figures incorporate the costs of collectors and auxiliary equipment (piping, ducting, wiring, instrumentation, and heat exchangers) as well as labor and other installation-related costs. System costs of flat plate and compound parabolic concentrators (CPC's) also include costs of short-term storage. Since storage was not used for industrial systems, flat plate and CPC costs for industrial process applications are $38/sq meter ($3.50/sq ft) less than the figures indicated in Table 13. (Industrial space heat systems were assumed to have short-term storage.)

TABLE 13. BASELINE INSTALLED COSTS[a]
1980 \$/m^2 (\$/ft^2)

	1980	1985	1995
Flat Plate	$390 ($36)	$350 ($32)	$310 ($29)
Compound Parabolic Concentrator	$520 ($48)	$480 ($44)	$400 ($37)
Parabolic Trough	$540 ($50)	$500 ($46)	$410 ($38)
Parabolic Disk	$1110 ($103)	$990 ($92)	$790 ($73)

[a] Costs incorporate collector and auxiliary equipment costs (including piping, wiring, instrumentation, heat exchangers, and, in the case of flat plate and CPC systems, short-term (1-3 days) thermal storage). Costs also reflect labor and other installation-related costs. Costs for FP and CPC systems in industry are \$38/m^2 (\$3.50 ft^2) lower than indicated above, because storage was not assumed for these systems.

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* Personal communication with John Davidson, Suntec, Inc.

**Some of the cost variability may be attributable to performance factors, e.g., more expensive, higher quality collectors. In such cases, energy output may be greater and costs on a $/GJ basis the same or lower.

Solar installed costs were determined by interviews with solar equipment manufacturers and installers, conversations with DOE personnel and DOE contractor agencies and laboratories, and an extensive literature review. Table 14 lists sources of our cost information; a bibliography in Appendix A indicates the literature sources reviewed. While there is no consensus regarding solar costs and while costs are extremely varied, the costs used in this study are believed to be reasonable averages. A range of collector costs were compared in the sensitivity analysis to assess solar market penetration under different cost assumptions.

The cost data do not distinguish between large and small systems, retrofit versus new systems, regional labor rate variation, etc. These factors were not addressed for two reasons: 1) the added detail would be prohibitive for a study of this scope, and 2) the available data are inadequate to discriminate between such factors with reasonable precision. It seems likely, for example, that regional labor variation may be important or that retrofits may be more costly than new installations, but the data are not conclusive. In the study alluded to earlier (King et al., 1979), new systems were found to cost 92 percent as much as retrofit systems on average. The authors concluded that retrofits were only slightly more expensive than new systems and that ".. the difference may even decrease as a larger sample of projects is obtained."* The study also evaluated scale economies and regional cost variations. It concluded "there were no appreciable scale economies and regional influences had not been significant in the sample analyzed." (King et al., 1979). The difference between new and retrofit system costs in industry also appear to be slight.**

The cost figures in Table 13 are expressed as collector system-related costs, rather than the prototypic systems defined previously. To determine prototypic system costs, the appropriate collector system-related cost for the system is used. Thus, hot water heating system costs, which employ flat plate collectors, would be $390/sq meter ($36/sq ft) for 1980. System heating and cooling, which use compound parabolic concentrators, would equal $540/sq meter ($50/sq ft) for 1980. Implicit in this procedure is the assumption that the type of collector is the most important factor differentiating costs between systems and can be used to scale the costs of other system components. Under this assumption, for example, the installed costs of industrial low temperature process systems (less than 121°C (250°F)) employing concentrating collectors would equal the installation cost of heating and cooling applications for commercial buildings (which also use CPC's). While there undoubtedly are differences in piping, ductwork, possibly instrumentation, and labor between these applications, EEA does

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* This may or may not be true. Retrofit demonstrations probably are not a representative sample. It is probable that only those buildings easily (and least expensively) retrofitted will be chosen for demonstration. Thus, more significant cost differences between retrofit systems may, in fact, exist.

**Personal communication with John Davidson, Suntec, Inc.

TABLE 14. SOURCES OF COST INFORMATION

DOE Affiliate Agencies and Laboratories

1) Solar Energy Research Institute
2) Sandia Laboratories
3) Lawrence Livermore Laboratory
4) Jet Propulsion Laboratory
5) Department of Energy Field Office, San Francisco
6) Lawrence Berkeley Laboratory

Solar Equipment Manufacturers and Installers

1) LOF Solar Energy Systems
2) Sunworks, Inc.
3) U.S. Solar
4) Grumman-Sunstream Products
5) Lennox Industries
6) Suntec, Inc.
7) Acurex, Inc.
8) Solaron Corporation
9) Owens Illinois, Inc.
10) Omni Corporation
11) Raypak, Inc.
12) Albuquerque Western, Inc.
13) Sunpower System Corp.
14) Solar Kinetics

not believe available data allow a reliable estimate of the difference. In terms of overall uncertainties, the error introduced by this assumption should not be significant.

The question of potential collector and installed cost improvement over time is a subject of some dispute. It is difficult to predict future installed cost improvements at the present time without making an assumption about solar market penetration. Some improvements in installation costs and procedures seem likely (Thayer et al., 1978). There are some theoretical reasons, however, for establishing boundaries for collector cost reductions (for thermal collectors), due to the fraction of collector costs embodied in materials costs.* In postulating thermal collector and installation reductions, EEA assumed larger cost reductions for less advanced collectors: that is, it was assumed that commercialized collectors (e.g., flat plates) more closely reflect their ultimate price than do collector systems still largely in an experimental stage (e.g., parabolic troughs). Solar system costs were varied in sensitivity analyses to assess effects of the cost assumptions.

System Financing

Financing parameters determine how installed system costs are perceived by the solar investor. Financing variables may be grouped into two categories: 1) basic assumptions of the analysis (inflation rate, level of O&M, form of life cycle cost expression, etc.) and 2) financial parameters which vary by investor type (ownership status, tax status, access to financing) .

Basic Assumptions --

Life Cycle Costing -- Solar systems costs were evaluated on a life cycle basis. Life cycle cost methodology captures the effects of capital opportunity costs and enables a cost/benefit assessment over a system's operating life. The approach is appropriate for solar system cost analysis where a large initial investment must be weighed against a long-term benefits.

Life cycle costs were expressed as a levelized annual cost which provides the uniform annual payment over a system's life equaling the net present value of the actual cash flow. Costs in this form facilitate the derivation of solar costs on a \$/GJ basis.**

While life cycle costing is the "appropriate" way of evaluating a solar investment, there are other commonly used evaluative techniques employed by residential home owners, commercial businesses, and industries. Payback period (in years) is a common criterion employed by all investor categories.

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* Personal communication with George Kannapol, Suntec, Inc.

**\$/GJ are derived by determining the gigajoules output per sq meter per year and dividing this into the annualized cost per square meter.

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Years to recover down payment or years to positive cash flow are commonly used by residential homeowners (Bezdek et al., 1979; ERDA, 1976). These techniques invariably result in a less favorable solar cost comparison than life cycle costing. Life cycle cost figures, therefore, may represent a best case in relation to other financial analysis methodologies. They are used only to evaluate a theoretical market potential, rather than as indicators of real world investor behavior.

O&M and Replacements -- O&M costs incorporate all operating and maintenance costs, including the energy costs of operating the solar system. Energy consumption of the system is mostly in the form of electricity for driving pumps and represents a small fraction of the total annualized system cost (Dickenson and Brown, 1979). A relatively high O&M value was adopted to account for the potential effect of electricity price escalation on overall O&M costs and potentially high maintenance costs due to uncertain system reliability (DOE, 1979a, 1979c, 1979d). Electricity prices in the reference AQCR's, for the most part, are projected to escalate only slightly in real terms.

Replacement of major system components was assumed not to occur during the 20-year system life. Because solar system operating experience is limited, the reliability and durability of solar system components (collectors, fittings on moving receivers, etc.) are not known. Sensitivity analyses evaluating different replacement assumptions showed that the assumed level of replacement exerts slight variation on overall system costs (due to the low present value of expenses in the latter part of the system life) (Dickenson and Brown, 1979). Therefore, ignoring replacements cannot be expected to significantly bias results.*

Inflation -- Inflation was not factored out of the analysis. It is fairly typical, in comparative analyses, to make comparisons in real dollar terms. Energy prices are escalated at a real (rather than nominal) rate while other cost items are held constant. Discount rates also are expressed in real rather than in nominal terms. EEA included inflation in the analysis because an error is introduced by ignoring it (Dickenson and Brown, 1979). The error occurs because depreciation deductions and loan repayment have a fixed value when expressed as current dollars (i.e., as dollars valued in the year of the repayment) while declining in real dollar terms. This is not captured if inflation is ignored.

EEA used a 6 percent inflation rate for all cost analyses. Since the analyses are comparative, an error in estimating inflation should not be serious (less significant than ignoring inflation entirely, provided that the rate of inflation is closer to 6 percent than 0 percent, which seems likely). The annualized cost procedure incorporating inflation results in the expression of costs in current year dollars; thus, 1985 costs are expressed in 1985 dollars, 1995 costs are expressed in 1995 dollars, etc.

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*Salvage value of the system was also assumed equal to zero. Even if the system does have some value after decommissioning, the net present value would be low.

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Financial Parameters Related to Investor Category --

1980 Baseline Parameters -- Financial parameters involving tax status, financing methods, and access to capital vary by investor category (see Table 15). For this study, three categories of solar investors were examined: 1) Federal, State, and municipal governments, 2) residential homeowners, and 3) private business (e.g., commercial building owners, industrial plant owners).

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Baseline values of financial parameters by investor category are indicated in Table 15. The 1980 values reflect current solar legislation: a 40 percent tax credit for residential heating and cooling and hot water systems and a 25 percent tax credit for commercial and industrial applications. These measures are due to expire in 1985. Congress passed solar bank legislation in June 1980, which was to make low interest loans available for solar investors beginning in 1981. The details of the loan mechanism (loan interest rates, loan periods) were not available when this study was initiated. However, the range of analysis in this report encompasses the interest levels proposed for solar bank low interest loans.

Many States and localities also have solar system legislation in place or pending. Solar incentives on the State level may include property tax exemptions and State income tax credits. Table 16 indicates the financial status of solar energy systems in States which encompas the reference AQCR's.

1985 and 1995 Financial Parameters -- Financial parameters for 1985 assume a continuation of modest (baseline) government promotion policy. For residential systems, it is assumed that the tax credit is scaled down from 40 percent to 20 percent, but that low interest loan financing (9.0 percent interest) becomes available. For commercial and industrial applications (private business), it is assumed that the 25 percent tax credit is renewed, that low interest loans (9.0 percent) are available, and that the low interest loan availability encourages some measure of debt financing (0.50 debt/0.50 equity). Baseline government parameters remain constant. (The effects of more attractive financing incentives in response to a deliberative governmental promotion policy are considered later in sensitivity analyses.)

The baseline financial parameters are averages for the investor categories. Most research shows a large degree of variability within each investor category (particularly for residential and business investors) for such parameters as tax status and discount rates. For example, the tax bracket (0.32) and discount rate (0.10) indicated for residential homeowners is typical of a family of four with an income $27,500. For lower income homeowners ($10,000 to $15,000 per year), income tax rates will be lower and discount rates much higher. Preliminary empirical research (Housman, 1979) indicates that the discount rates used by homeowners in the $10,000 to $15,000 range are on the order of 33 percent. The value of loan interest and property tax deductions also differ between low and high income groups. Thus, the discount rate and tax status assumptions utilized

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TABLE 15. BASELINE (1980) FINANCING ASSUMPTIONS

Applicable Parameter	Investor		
	Government	Homeowner	Private Business
Discount rate	0.10	0.10	0.15
Loan fraction		0.85	0.30 (0.50)*
Loan interest rate		0.12 (0.09)*	0.12 (0.09)*
Loan period**		20.0	20.0
Composite income tax rate		0.32	0.50
Investment tax credit		0.40 (0.20)*	0.25
Inflation rate	0.06	0.06	0.06
Depreciation method			SOYD***
Depreciation period			7.0
System life	20.0	20.0	20.0
O & M§	0.04	0.035	0.04
Replacement	0.0	0.0	0.0
Net salvage value	0.0	0.0	0.0
Property tax		0.0	0.0

* Financial parameters for 1985 and 1995 in parentheses.

** The 20-year loan period is a compromise between common 20-30 year new house mortgage financing and the 10-20 years for commercial loans, home improvement loans, or second mortgages. While this financing period assumption may be longer than the conventional technical lifetime assumption for domestic water heating systems, the longer loan period does not significantly alter the comparative economics of solar systems.

***Sum-of-year digits.

§ O & M costs are expressed as percentages of total installed system costs.

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TABLE 16. STATE SOLAR ENERGY INCENTIVES

		Type of Incentive*		
AQCR	State	Income Tax Credit	Sales Tax Exemption	Property Tax Exemption
Chicago	Illinois	None	None	Assessed value of collector (residential and commercial)
	Indiana	25% credit up to $3000, residential up to $10,000, commercial	None	None
Philadelphia	Pennsylvania	Proposed	None	None
	New Jersey	None	5% tax	None
	Delaware**	$200 credit for certain active residential hot water systems	None	None
Houston	Texas***	None	6% tax	None

* Sources of data for this table include: Illinois Institute of Natural Resources; Indiana Department of Commerce (Energy Group); Pennsylvania Energy Office; New Jersey Department of Energy; Delaware Energy Office; and Texas Energy Office.

** Delaware has proposed a solar grant program.

***Texas has a franchise tax exemption for solar distributors and retailers.

for the base case as representative probably present a somewhat optimistic picture of residential solar financing.*

Another fact not captured in the case of residential financial assumptions is the distinction between new and retrofit financing. The baseline assumptions are for a new system. Retrofit heating and cooling systems would generally be financed by a second mortgage because installed costs usually exceed the limits for home improvement loans. Hot water heating systems could probably be financed by a home improvement loan. The difference between financing a new system as part of a mortgage and financing a retrofit system with a second mortgage probably would not be significant, given similarities in interest rates and the small difference between the discount rates assumed on the equity portion of the new investment (0.10) and loan interest (0.12). Home improvement loans may have higher interest rates and shorter loan periods, however. The resulting difference is not captured by the average baseline values.

Likewise, there are differences within the commercial and industrial sectors that are averaged to obtain the baseline assumptions. A double declining depreciation schedule may be used for depreciating apartment heating and cooling equipment if the apartment building is owned by one individual. If the same building is multiply owned, however, only a 1.25 declining schedule is allowed (OTA, 1978). A double declining balance schedule or equivalent (sum-of-year digits) is allowed for depreciating most industrial equipment. However, the depreciation period will vary, depending on the particular equipment concerned. The IRS has not yet established guidelines for the depreciable life of solar equipment (Dickenson and Brown, 1979).

Annualized System Costs

Using the baseline financial assumptions, an annualized cost multiplier was determined for each investor category to convert capital costs into annualized system costs. Baseline annualized costs are indicated in Table 17 for the three reference years.

SYSTEM OUTPUT AND VALUE

Up to this point, the costs of solar energy have been considered independently of the energy performance characteristics of the system. The system energy output and fuel price are the additional elements required to express solar energy cost as a relative attractiveness ratio. The output of solar systems for each end use was determined in Section 5. These figures, scaled to reflect end-use load characteristics of the application and conversion efficiencies of conventional equipment, were combined with

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*Since the equity (down payment portion) of the system is small, 15 percent, the effects of the low discount rate are only reflected on 15 percent of the system cost. Also, since a property tax exemption was assumed for the baseline, the differential effects of tax status on the value of property tax deductions is eliminated.

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TABLE 17. BASE CASE SYSTEM COSTS*

		Annualized System Cost $/m² ($/ft²)			
Year	System	Residential	Commercial	Public	Industrial
1980	Flat Plate	$49** ($4.5)	$61 ($5.6)	$68 ($6.3)	$60*** ($5.6)
	Compound Parabolic Concentrator	---	81 (7.5)	91 (8.4)	81*** (7.5)
	Parabolic Trough	---	---	---	85 (7.8)
	Parabolic Dish	---	---	---	175 (16.1)
1985	FP	49 (4.5)	54 (5.0)	60 (5.6)	54*** (5.0)
	CPC	---	73 (6.8)	83 (7.7)	73*** (6.8)
	PT	---	---	---	76 (7.1)
	PD	---	---	---	153 (14.2)
1995	FP	84 (7.6)	86 (8.0)	98 (9.1)	86 (8.0)
	CPC	---	110 (10.2)	125 (11.6)	110 (10.2)
	PT	---	---	---	113 (10.5)
	PD	---	---	---	217 (20.1)

* Costs expressed in dollars of the reference year. Inflation rate is assumed to equal 6%.

** The low baseline residential costs, relative to the other sectors, reflect the effects of a 40% tax credit, now currently in place for homeowners. Commercial and industrial systems are permitted a 25% tax credit. All tax credits are due to expire in the 19851986 timeframe. For purposes of this analysis, it was assumed (for the base case) that the residential credit would be renewed at a 25% rate and the commercial and industrial credits likewise would be extended at 25%.

***These costs are for industrial water heating and space heating systems; that is, storage costs are reduced. Costs of process applications employing FP & CPC collectors are lower by from 7 to 12%.

the annualized system cost/sq meter figures (above) to determine a $/GJ cost for each end use. This figure was then divided by the fuel cost per GJ for each conventional fuel utilized for the end use to derive the relative attractiveness ratio.

Fossil fuel price projections were based on DOE's mid-range energy forecasting (MEFS) projection series B. Price projections for 20-year periods beginning in the reference years (i.e., 1985 to 2005 and 1995 to 2015) were levelized and discounted by the weighted cost of capital of the solar system compared to the relative attractiveness ratio. Table 18 indicates the period average fuel price for the 1985 to 2005 and 1995 to 2015 life cycles. Electricity prices remain fairly constant, while gas and oil prices increase.

TABLE 18. PROJECTED USER ENERGY PRICES*
(1980 $/GJ)**

Sector/Fuel	1985-2000*** Philadelphia	1985-2000*** Chicago	1985-2000*** Houston	1995-2015*** Phildelphia	1995-2015*** Chicago	1995-2015*** Houston
Residential						
Electricity	16.11	15.44	16.88	16.68	16.14	17.30
Gas	5.54	5.07	5.47	6.59	6.45	6.89
Oil	8.88	8.41	8.85	10.99	10.58	11.14
Commercial, Public						
Electricity	15.22	15.19	15.76	15.77	16.01	16.16
Gas	5.02	4.70	4.86	6.21	6.06	6.29
Oil	8.44	8.19	8.36	10.51	10.38	10.52
Industrial						
Electricity	11.82	11.14	12.76	12.65	11.94	13.12
Gas	7.15	5.95	4.54	12.02	7.28	5.97
Oil	8.57	8.20	8.34	10.59	10.38	10.47
Coal	2.56	2.56	2.51	3.14	2.72	2.83

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* These are base fuel prices (unlevelized or discounted) in 1980 dollars. They illustrate the relative price difference between fuels and across regions.

** 1 GJ = 0.948 x 10^6 Btu.

***Prices are period averages.

SECTION 7

MARKET CAPTURE AND FUEL DISPLACEMENT

METHODOLOGY OVERVIEW

Market capture and fuel displacement were based on calculated RAR's for each end use and fuel type combination (market segment). When an RAR exceeds one, the solar system is competitive by definition. No attempt was made at postulating market penetration rates in the solar competitive segments to determine fuel displacement. Rather, when a solar system was competitive, the entire energy base of the competitive segment, adjusted by a solar load factor, was considered displaced. Therefore, fuel displacement does not represent predictions based on projected market penetration. Instead, fuel displacement represents the theoretical maximum solar substitution based on technical (load) and economic factors. Actual fuel displacement will be lower, given institutional constraints, information gaps, and competition with alternative fuels or conservation technologies that may force delays and/or additionally limit the penetration of solar technologies.

Total sector fuel displacement was calculated in a several stage process:

- Solar competitive market segments were identified. For the Chicago residential sector in 1995, the solar competitive segments are electric, gas, and oil hot water heating and oil space heating for single family attached homes; gas, oil, and electric hot water heating systems for single family detached homes; and oil and electric hot water heating for multi-family high rises.

- Energy consumption within each competitive segment is adjusted by a solar load factor.

- Fuel displacement is calculated by summing the load adjusted energy base of each of the segments by fuel type to achieve a partial sector total. Tables 19, 20, and 21 show calculations for electricity, gas, and oil, respectively, for the 1995 Chicago residential sector. The summation process results in 4.50 PJ (4.27×10^{12} Btu) of electricity, 26.1 PJ (24.7×10^{12} Btu) of gas, and 0.32 PJ (0.31×10^{12} Btu) of residential oil displacement.

TABLE 19. ELECTRICITY DISPLACEMENT, CHICAGO, 1995
PJ (10^{12} Btu)*

Type of Structure	Total Consumption	Market Capture (RAR>1)	Total Fuel Displacement**
Single Family Detached			
Water Heating	7.43 (7.04)	Yes	4.22 (4.00)
Space Heating	12.77 (12.10)	No	0.0
Single Family Attached			
Water Heating	0.22 (0.21)	Yes	0.09 (0.09)
Space Heating	0.29 (0.28)	No	0.0
MultiFamily High Rise			
Water Heating	0.39 (0.37)	Yes	0.19 (0.18)
Space Heating	0.6 (0.6)	No***	0.0
Total Fuel Displacement			4.50 (4.27)

* 1 PJ = 0.948 x 10^{12} Btu.

** Total fuel displacement resulting from optimal solar system penetration of the full market cell.

***Space heating was not considered for the MFH prototype structure due to a lack of sufficient roof area.

TABLE 20. GAS DISPLACEMENT, CHICAGO, 1995
PJ (10^{12} Btu)*

Type of Structure	Total Consumption	Market Capture (RAR>1)	Total Fuel Displacement**
Single Family Detached			
Water Heating	44.35 (42.04)	Yes	25.78 (23.96)
Space Heating	296.54 (281.08)	No	0.0
Single Family Attached			
Water Heating	1.82 (1.72)	Yes	0.78 (0.74)
Space Heating	7.01 (6.64)	No	0.0
MultiFamily High Rise			
Water Heating	3.46 (3.28)	No	0.0
Space Heating	6.62 (6.27)	No***	0.0
Total Fuel Displacement			26.06 (24.70)

* 1 PJ = 0.948 x 10^{12} Btu.

** Total fuel displacement resulting from optimal solar system penetration of the full market cell.

***Space heating was not considered for the MFH prototype structure due to a lack of sufficient roof area.

TABLE 21. OIL DISPLACEMENT, CHICAGO, 1995
PJ (10^{12} Btu)*

Type of Structure	Total Consumption	Market Capture (RAR>1)	Total Fuel Displacement**
Single Family Detached			
Water Heating	0.39 (0.37)	Yes	0.22 (0.21)
Space Heating	41.78 (39.60)	No	0.0
Single Family Attached			
Water Heating	negligable	Yes	0.0
Space Heating	0.96 (0.91)	Yes	0.09 (.09)
MultiFamily High Rise			
Water Heating	0.02 (0.02)	Yes	0.01 (0.01)
Space Heating	0.79 (0.75)	No***	0.0
Total Fuel Displacement			0.32 (0.31)

* 1 PJ = 0.948 x 10^{12} Btu.

** Total fuel displacement resulting from optimal solar system penetration of the full market cell.

***Space heating was not considered for the MFH prototype structure due to a lack of sufficient roof area.

- Since the prototypic structures account for 80 percent of total residential energy consumption, the fuel displacement figures are divided by 0.8 to estimate a sector total. That is, it is assumed that the absolute and relative amount of gas, oil, and electricity displaced by the prototypic structure reflects the sector total proportionately.

This procedure was followed for all sectors.

RESULTS

Residential and Commercial Sectors

For the residential and commercial sectors, fuel displacement occurred in all ACQR's for the 1985 and 1995 reference years (see Figure 7).

The fuel displacement indicated is a function of 1) solar competitiveness and market capture and 2) the size of the fuel base of the captured market. For example, the difference between electric and gas for all AQCR's in 1985 is a function of differential competitiveness; electric systems are competitive, gas systems are not (see Figure 7).

The results of the base case fuel displacement scenario are as follows:

1. In 1985, 95 percent of the fuel displacement resulted from capturing oil and electric hot water heating markets.

2. The penetration of solar hot water heating did not vary as much between AQCR's as the penetration for solar space heating systems. This occurred primarily because climates for these three AQCR's varied much more than hot water demand or ground water temperatures.

3. Fuel displacement increased in 1995 under the base case scenario. Solar systems become competitive with electric and oil space heating in Philadelphia and Chicago and with gas hot water heating in all AQCR's. Space heating systems are less competitive in the Houston AQCR because of the short and mild heating season.

4. Most fuel displacement occurred in the residential sector, because of the size of the residential water heating market. In the case of heating, both the size of the market and the competitiveness of residential solar systems relative to some parts of the commercial sector (e.g., public buildings) account for the larger residential share.

5. Space cooling systems were not competitive under the base case scenario.

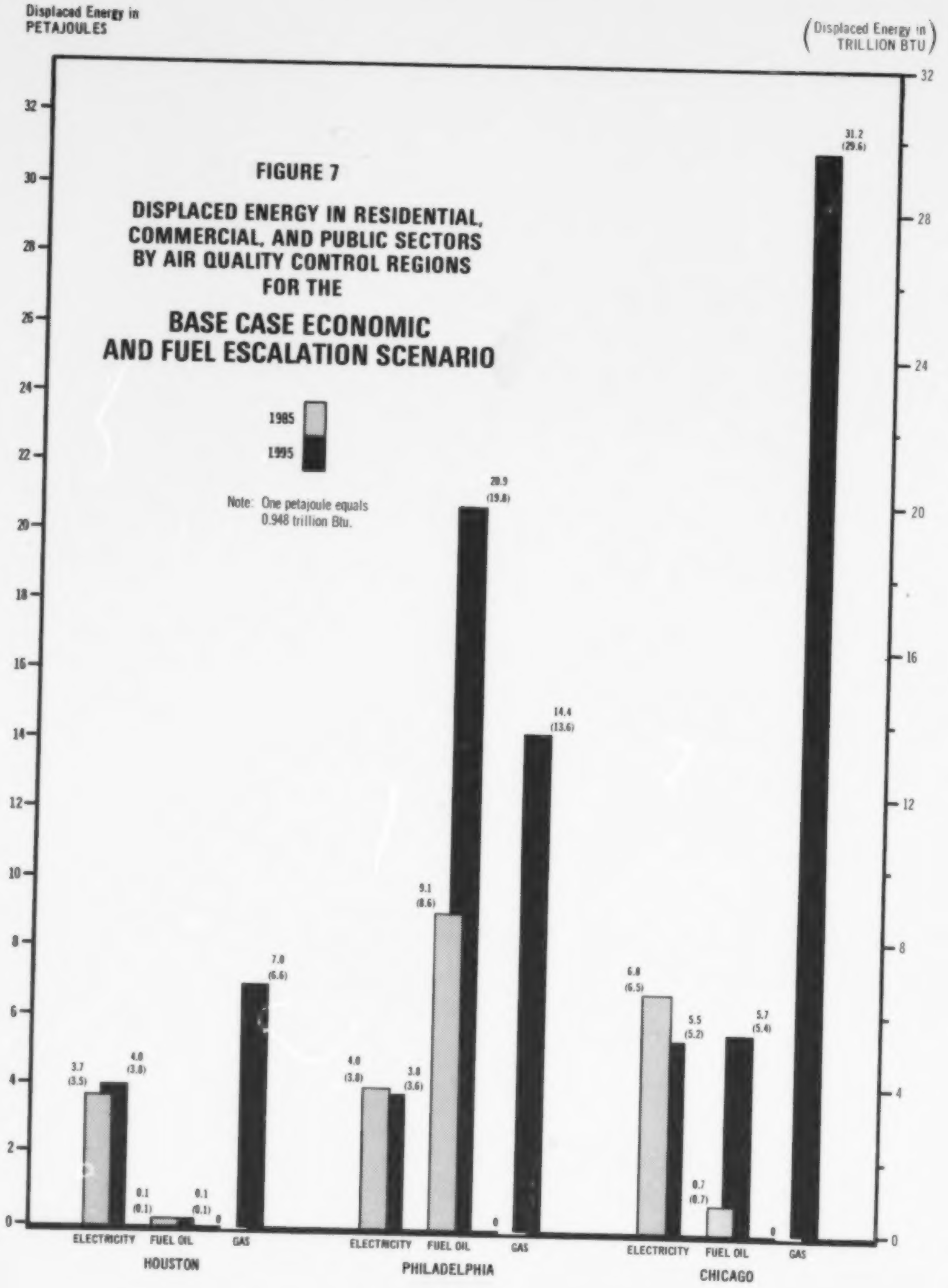

FIGURE 7

DISPLACED ENERGY IN RESIDENTIAL, COMMERCIAL, AND PUBLIC SECTORS BY AIR QUALITY CONTROL REGIONS FOR THE

BASE CASE ECONOMIC AND FUEL ESCALATION SCENARIO

Note: One petajoule equals 0.948 trillion Btu.

6. The base case fuel displacement level does not represent a large share of the total AQCR residential and commercial energy consumption. Fuel displaced in the Houston, Philadelphia, and Chicago AQCR's represented 1.43 percent, 1.79 percent, and 0.7 percent, respectively, of total residential and commercial energy consumption for 1985. (The Chicago percentage is low because of the small fraction of water heating energy consumption accounted for by oil and electricity, the competitive fuels in 1985.) Comparable figures for 1995 are 3.45 percent, 4.94 percent, and 4.33 percent.

7. The low base case fuel displacement reflects the small size of the hot water heating market (particularly for commercial and public buildings) and solar load fractions of 40 to 60 percent. While space heating loads are considerably larger, the economically optimal sized systems only meet 10 to 20 percent of the total load.

Industrial Sector

Base case fuel displacement was smaller in the industrial sector than in the residential, commercial and public sectors. Industrial solar systems are not competitive with any fuel type in 1985. In 1995, hot water process applications at 100°C (212°F) become competitive with gas and oil in Philadelphia and with oil in Houston. Unlike the residential and commercial sectors, industrial fuel prices vary between AQCR's producing different degrees of competitiveness. (Gas prices in Philadelphia are substantially higher than in Houston -- close to 50 percent in 1995 -- and oil prices are higher in Houston and Philadelphia than in Chicago). Industrial fuel displacement in 1995 in Philadelphia totalled 1.7 petajoules (1.6 trillion Btu), 0.4 percent of total AQCR industrial energy consumption. In Houston, 1.08 petajoules (1.02 trillion Btu) of fuel displacement amounts to only 0.07 percent of 1995 industrial consumption. Fuel displacement in the Philadelphia AQCR is larger in relative terms than for Houston because the potentially displaceable (technically viable) energy base represents a larger fraction of the total AQCR energy consumption in Philadelphia; 80 percent of Houston's industrial energy consumption is accounted for by two non-solar viable SIC's, 28 (Organic Chemicals) and 29 (Petroleum Refining).

Four factors account for the generally low (in relative terms) base case fuel displacement levels occurring in the industrial sector for all of the AQCR's: 1) the initial limitation of solar systems to 12 solar viable SIC's, 2) industrial coal use, with which solar is not competitive, 3) limited low temperature process water applications, the only solar competitive application in the base case, and 4) the solar load fraction, which was calculated as a weighted average between boilers and non-boilers for the 12 solar viable SIC's. Solar load fractions vary from 8 to 12 percent. Table 22 illustrates how these four factors progressively narrow the initial industrial consumption base for Philadelphia (405 petajoules) to the fuel displacement total calculated in 1995 (1.7 petajoules).

TABLE 22. PHILADELPHIA INDUSTRIAL FUEL CONSUMPTION DISPLACEMENT, 1995

	Fuel Base PJ (10^{12} Btu)*	% of Total
Total industrial base	405 (384)	100
Technically viable base	46 (44)	11.5
Minus coal consumption (13.3 x 10^{12} Btu)	32.4 (30.7)	7.9
Minus non-hot process water consumption	14.2 (13.5)	3.5
Adjusted by solar load factor (12%)	1.7 (1.6)	0.4

*1 PJ = 0.948 x 10^{12} Btu.

SENSITIVITY ANALYSIS

Overview

There are numerous uncertainties in solar system cost estimation and fuel price projections, as noted in previous sections. Sensitivity analyses were performed which varied key solar cost and fuel price assumptions. The basic objective of the sensitivity runs was to determine how fuel displacement would be affected by different economic assumptions and to establish a fuel displacement range to bracket solar fuel displacement potential. Of particular interest was the upper limit to fuel displacement.

Six scenarios were constructed by pairing three solar cost estimates (low, medium, and high) with two alternate fuel price projections (low and high). The scenarios are defined in Table 23. They are:

- Low Solar Cost, DOE (mid-range) Fuel Price Projection. Scenario 1 represents the government support case. For homeowners, a low interest government loan mechanism is assumed that makes loans available at 6 percent. A 40 percent tax credit is assumed. For business (commercial and industrial sector investors) it is assumed that a 50 percent tax credit is in place, that low interest 9 percent loans are available, and that low interest loan availability encourages a degree of debt financing (0.50 debt/0.50 equity). For the public sector, it is assumed that a 6 percent discount rate is stipulated for evaluating solar investments. (Historically, Federal agencies developing water projects, advanced coal conversion projects, or other projects the government wishes to promote are allowed to use low discount rates; likewise, on a municipal level, municipal bond financing (White, 1979) permits discount rates of around 6 percent.)

TABLE 23. SENSITIVITY SCENARIOS

Scenario	Solar Cost	Fuel Price
1.	Low	DOE projection
2. (Base Case)	Medium	DOE projection
3.	High	DOE projection
4.	Low	2% escalated
5.	Medium	2% escalated
6.	High	2% escalated

Unit collector cost reductions and improvements in installation procedures also are postulated. Installed costs were reduced (in real terms) between 1980 and 1995 from 30 to 45 percent. Table 24 indicates the difference between solar cost scenarios for 1985 and 1995 for the industrial sector.

- Average Solar Cost, DOE (mid-range) Fuel Price Projection. Scenario 2 is the base case scenario previously analyzed. In the spectrum of sensitivity scenarios evaluated, it represents a moderate solar cost (moderate government support) and DOE (mid-range) fuel price escalation.

- High Solar Cost, DOE (mid-range) Fuel Price Projection. In Scenario 3, no government support is assumed in terms of tax credits, low interest loans, or other subsidies. It is assumed that a moderate (current level) government-supported RD&D program lowers unit collector costs of parabolic troughs and dishes by 10 percent and 17 percent, respectively (in real terms), from 1980 to 1985. Flat plate and compound parabolic concentrator costs stay relatively constant in real terms. Fuel prices escalate at the lower rate. This scenario represents the solar worst case.

- Scenarios 4, 5, and 6 are the above solar cost estimates paired with fuel prices escalated at a 2 percent compounded rate above the DOE fuel price projection.

In total, the sensitivity scenarios consist of three cases more favorable than the base case, one case clearly less favorable, and one case of uncertain difference. The favorable scenarios are: base case average solar cost, 2 percent escalated fuel price projection (Scenario 5); low solar cost, DOE (mid-range) fuel price projection (Scenario 1); and, (most favorable of all) low solar cost, 2 percent escalated fuel price projection (Scenario 4). The latter was the solar best case. The clearly less favorable scenario is

TABLE 24. SOLAR SYSTEM COSTS FOR THE INDUSTRIAL SECTOR

Year	System	Solar Cost Scenario	Annualized Cost $/m²	($/ft²)
1980	FP	-	60.5	(5.6)
	CPC	-	81.0	(7.5)
	PT	-	82.2	(7.8)
	PD	-	173.9	(16.1)
1985	FP	Low	20.5	(1.9)
		Medium	52.9	(4.9)
		High	94.0	(8.7)
	CPC	Low	27.0	(2.5)
		Medium	73.4	(6.8)
		High	131.8	(12.2)
	PT	Low	29.2	(2.7)
		Medium	76.7	(7.1)
		High	137.2	(12.7)
	PD	Low	55.1	(5.1)
		Medium	153.4	(14.2)
		High	268.9	(24.9)
1995	FP	Low	29.2	(2.7)
		Medium	85.3	(7.9)
		High	158.8	(14.7)
	CPC	Low	37.8	(3.5)
		Medium	110.2	(10.2)
		High	220.3	(20.4)
	PT	Low	38.9	(3.6)
		Medium	113.4	(10.5)
		High	231.1	(21.4)
	PD	Low	62.6	(5.8)
		Medium	217.1	(20.1)
		High	435.2	(40.3)

FP = Flat plate
CPC = Concentrating parabolic collector
PT = Parabolic trough
PD = Point focusing dish

the high solar cost, DOE (mid-range) fuel price projection scenario (Scenario 3). The scenario of uncertain difference is the high solar cost, 2 percent escalated fuel price scenario (Scenario 6).

Residential and Commercial Results

Electricity displacement (Figures 8 and 9) increased slightly under the more favorable scenarios, which make solar competitive with electric heating. The difference between base case and the more favorable scenarios was not as pronounced in 1995 as in 1985 for Philadelphia and Chicago because solar heating in these AQCR's is competitive even under the base case scenario. For Houston, the difference was marked, because solar heating systems are not competitive in the base case.

Fuel oil displacement increases sharply in 1985 for Philadelphia and Chicago, with the addition of space heat markets under the favorable cost scenarios (Figures 10 and 11). Fuel oil space heat markets are sizeable, so the capture of space heat markets more than doubles fuel displacement. In 1995, the favorable scenarios also encourage more fuel displacement in Philadelphia and Chicago, as public and some commercial applications become competitive. For Houston, residential and commercial fuel oil markets are so small that differences between scenarios do not significantly affect total fuel displacement.

Gas displacement is most affected by the favorable solar scenarios (Figures 12 and 13). Under the base case scenario, no gas is displaced in 1985. Hot water heating and some gas space heat markets are captured under the best case (low solar cost, high fuel cost scenario) in 1985. For Chicago, this increases fuel displacement to 88.1 petajoules (83.5 trillion Btu). Gas displacement also increases in 1995, due to the added capture of gas space heat markets in all AQCR's.

In the aggregate, for 1985, fuel displacement between the base case and best case increased 223, 843, and 352 percent in Houston, Chicago, and Philadelphia, respectively. These dramatic percentage increases are primarily a function of the small size of the base case solar fuel displacement. The fraction of total commercial and residential energy consumption accounted for in the most favorable case is 3.2 percent, 5.9 percent, and 6.3 percent for Houston, Chicago, and Philadelphia, respectively, in 1985. The gap between Houston and Philadelphia/Chicago is the continued attractiveness of gas heating in Houston under any scenario.

In 1995, the change from base case to best case was less pronounced, but the overall fraction of energy displaced in the best case was larger. Total fuel displacement of the best case was 8.6 percent, 10.7 percent, and 8.5 percent for Houston, Chicago, and Philadelphia, respectively.*

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*These figures do not include fuel displacement from space cooling systems. This was not calculated, for reasons outlined in Appendix B.

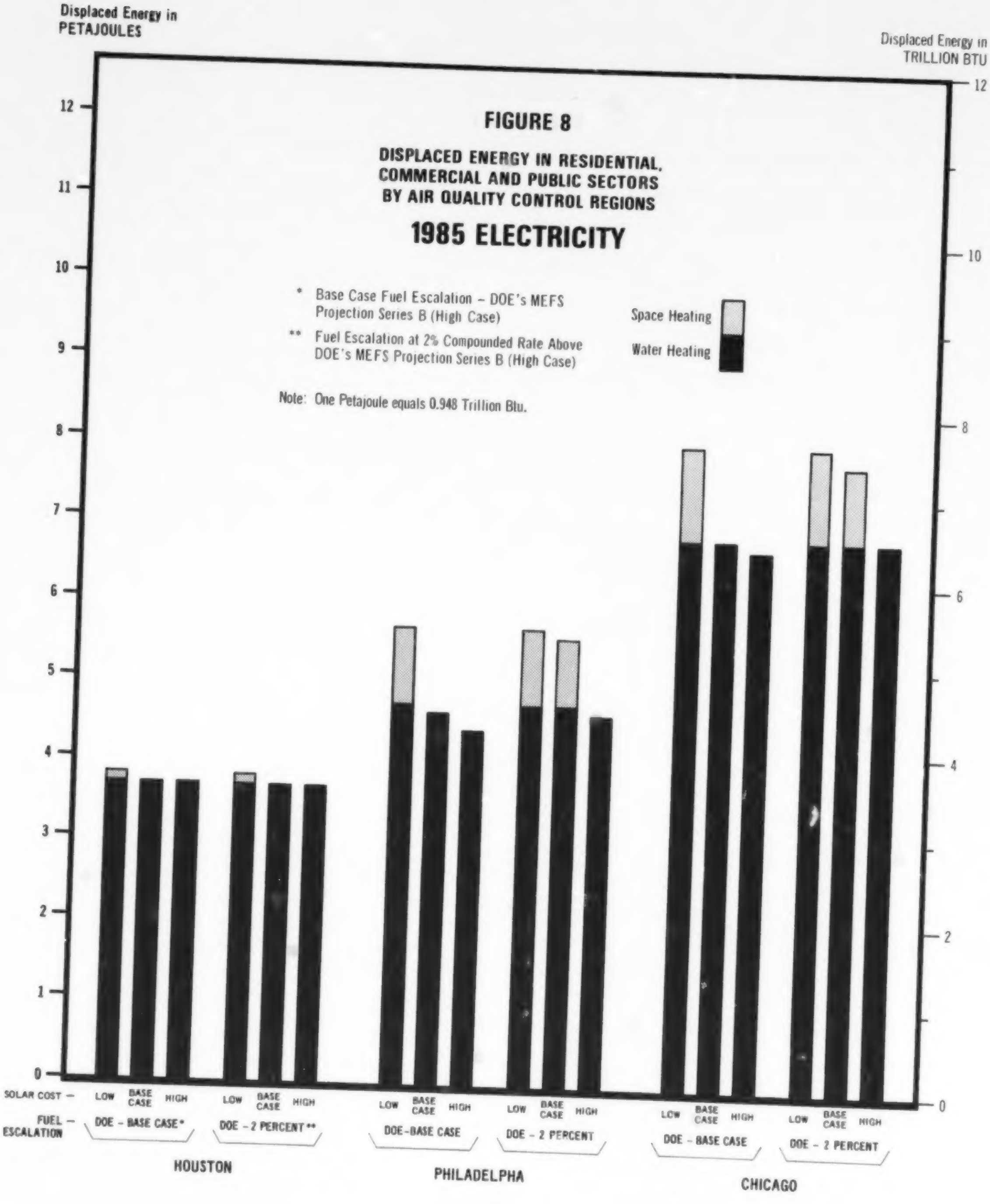


FIGURE 8

DISPLACED ENERGY IN RESIDENTIAL, COMMERCIAL AND PUBLIC SECTORS BY AIR QUALITY CONTROL REGIONS

1985 ELECTRICITY

* Base Case Fuel Escalation – DOE's MEFS Projection Series B (High Case)

** Fuel Escalation at 2% Compounded Rate Above DOE's MEFS Projection Series B (High Case)

Note: One Petajoule equals 0.948 Trillion Btu.

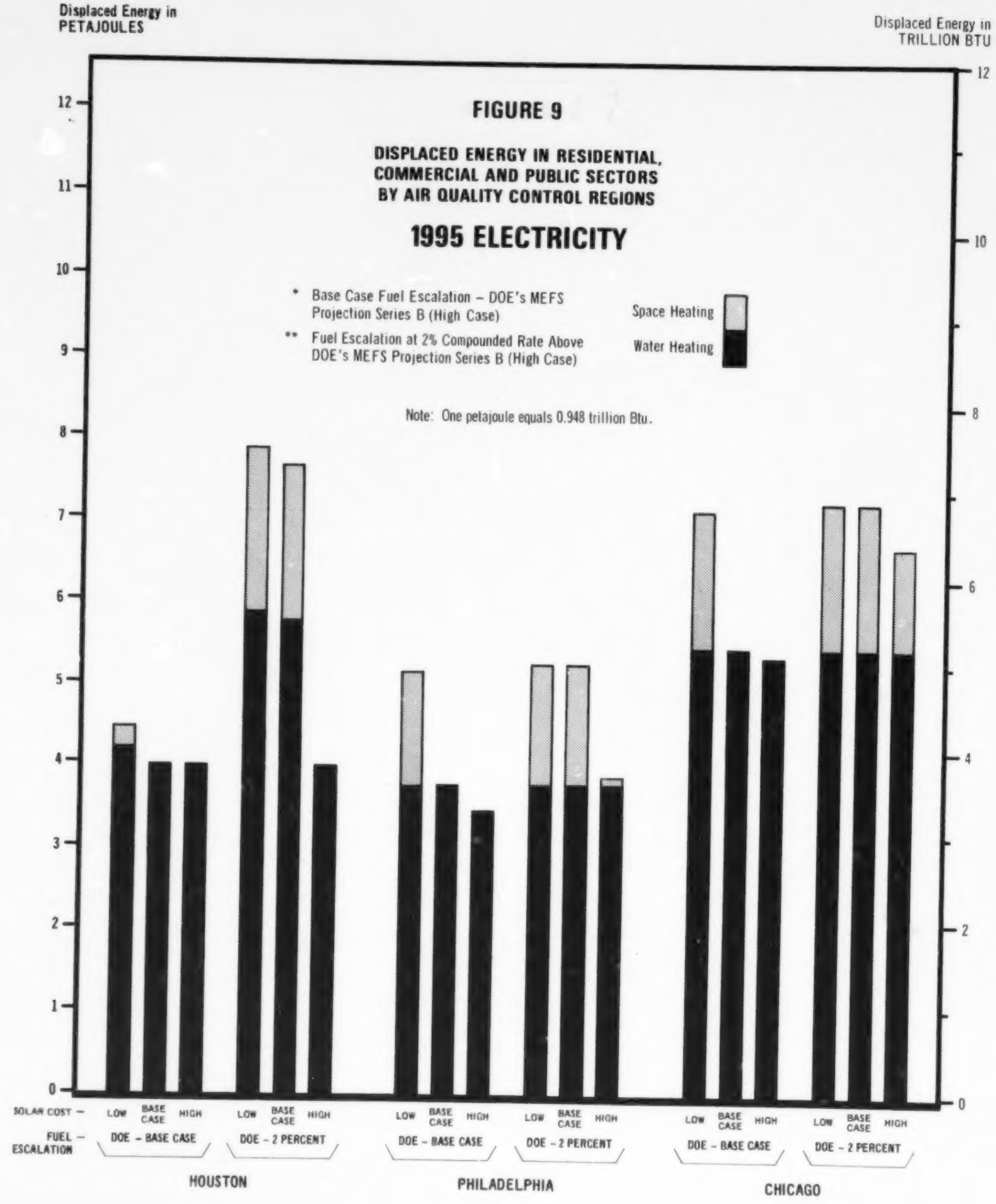


FIGURE 9

DISPLACED ENERGY IN RESIDENTIAL, COMMERCIAL AND PUBLIC SECTORS BY AIR QUALITY CONTROL REGIONS

1995 ELECTRICITY

* Base Case Fuel Escalation – DOE's MEFS Projection Series B (High Case)

** Fuel Escalation at 2% Compounded Rate Above DOE's MEFS Projection Series B (High Case)

Space Heating ▨

Water Heating ■

Note: One petajoule equals 0.948 trillion Btu.

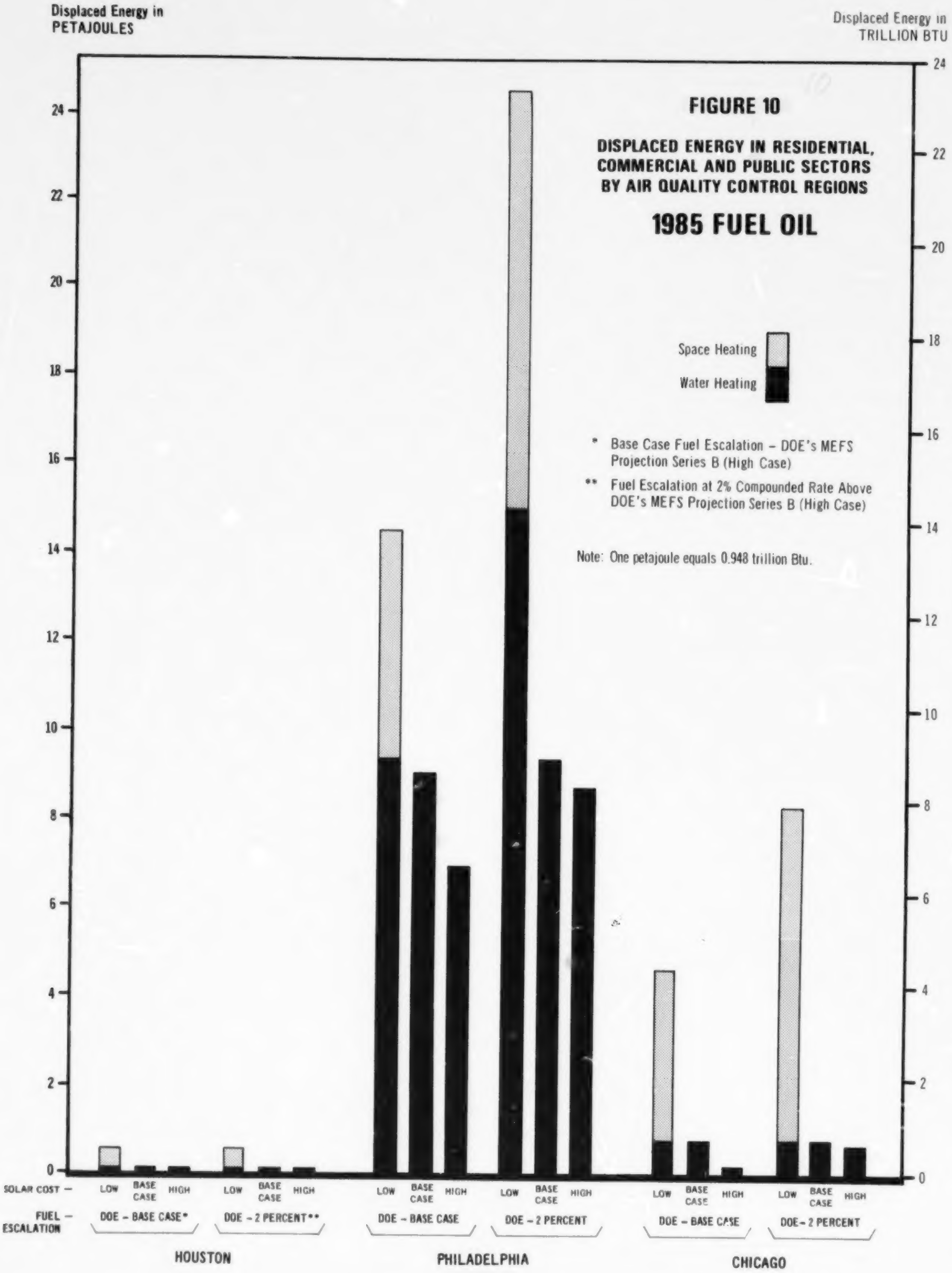


FIGURE 10

DISPLACED ENERGY IN RESIDENTIAL, COMMERCIAL AND PUBLIC SECTORS BY AIR QUALITY CONTROL REGIONS

1985 FUEL OIL

* Base Case Fuel Escalation – DOE's MEFS Projection Series B (High Case)

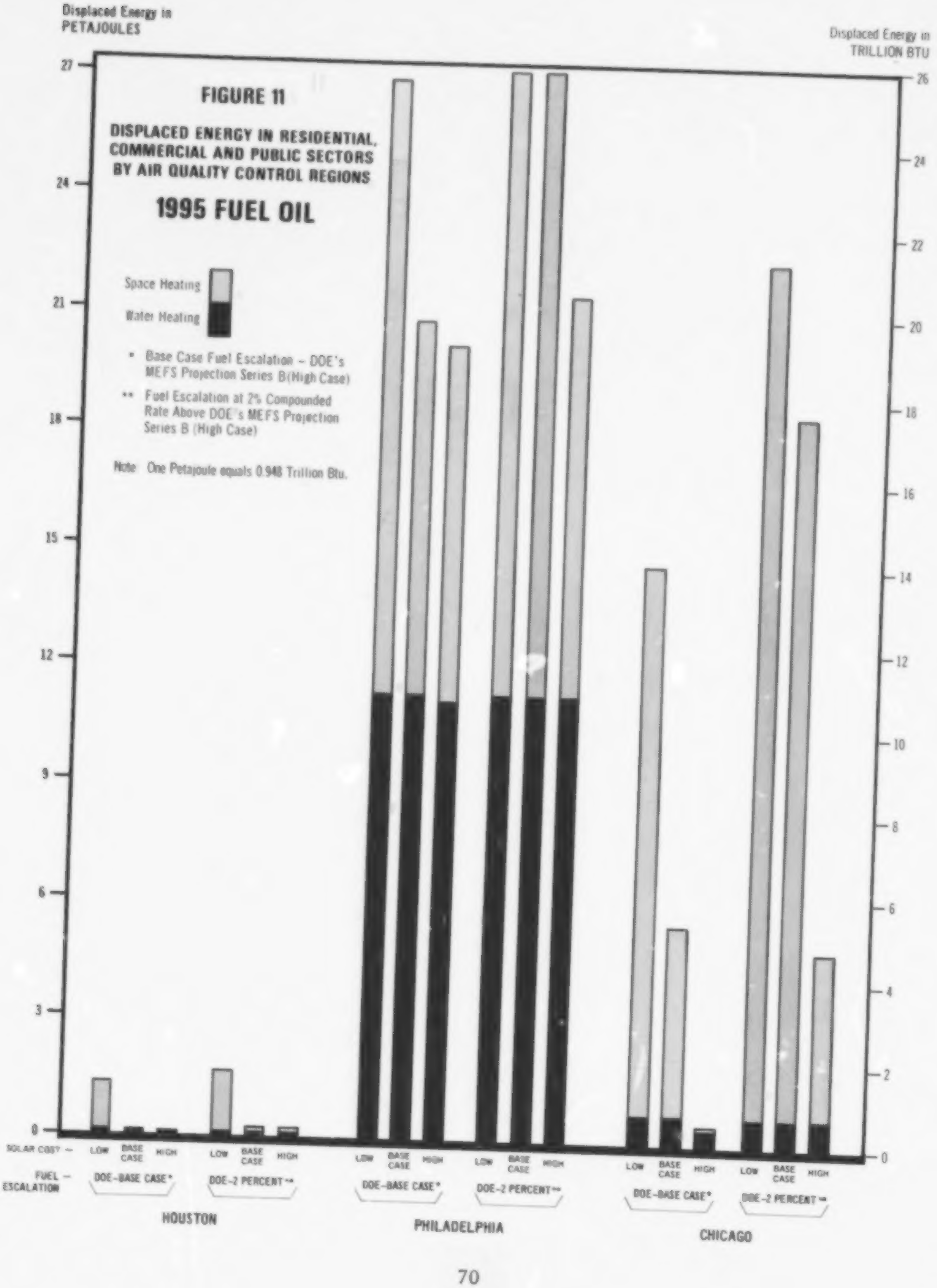
** Fuel Escalation at 2% Compounded Rate Above DOE's MEFS Projection Series B (High Case)

Note: One petajoule equals 0.948 trillion Btu.

FIGURE 11

DISPLACED ENERGY IN RESIDENTIAL, COMMERCIAL AND PUBLIC SECTORS BY AIR QUALITY CONTROL REGIONS

1995 FUEL OIL



* Base Case Fuel Escalation – DOE's MEFS Projection Series B (High Case)

** Fuel Escalation at 2% Compounded Rate Above DOE's MEFS Projection Series B (High Case)

Note: One Petajoule equals 0.948 Trillion Btu.

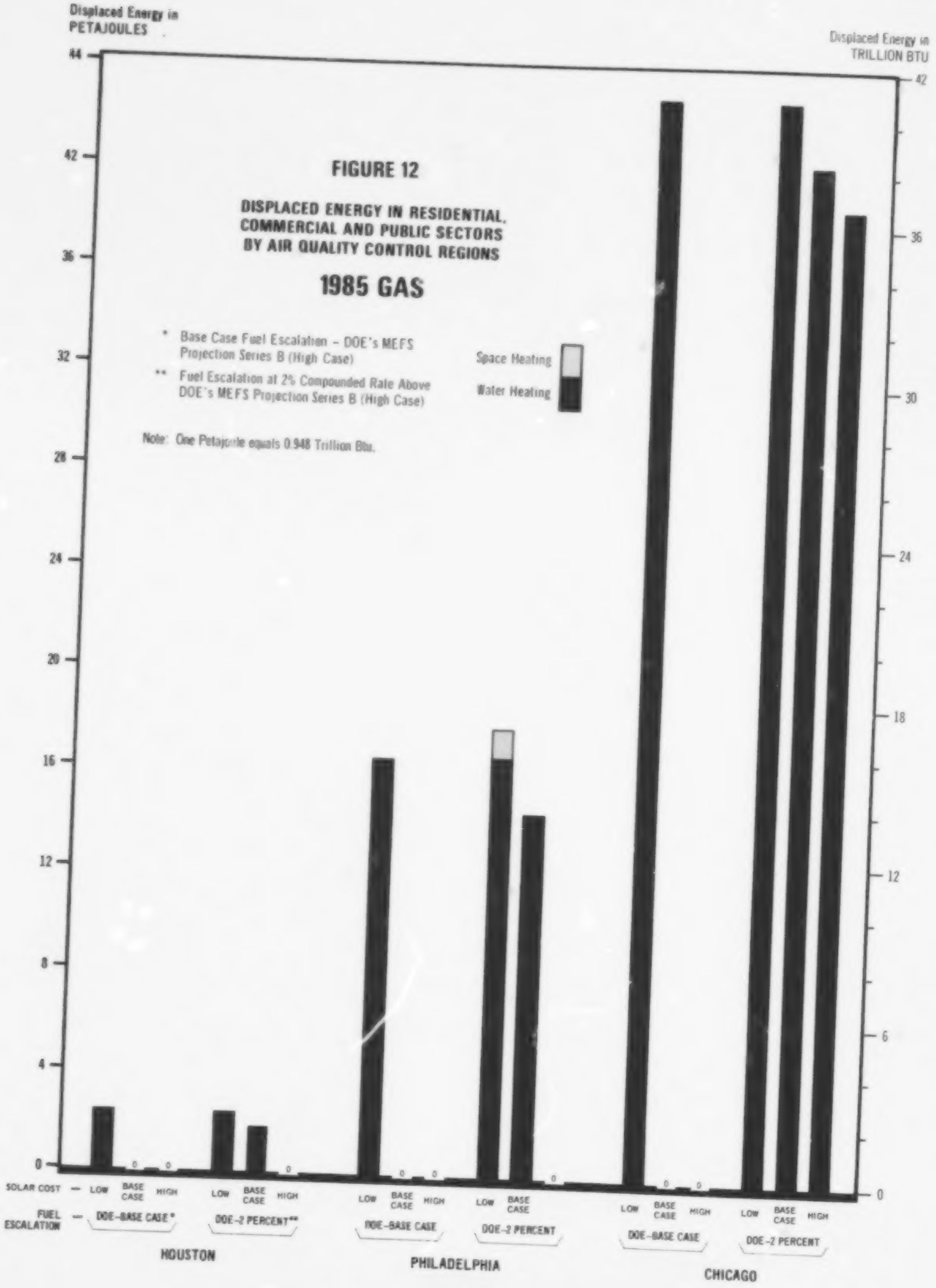


FIGURE 12

DISPLACED ENERGY IN RESIDENTIAL, COMMERCIAL AND PUBLIC SECTORS BY AIR QUALITY CONTROL REGIONS

1985 GAS

* Base Case Fuel Escalation – DOE's MEFS Projection Series B (High Case)

** Fuel Escalation at 2% Compounded Rate Above DOE's MEFS Projection Series B (High Case)

Note: One Petajoule equals 0.948 Trillion Btu.

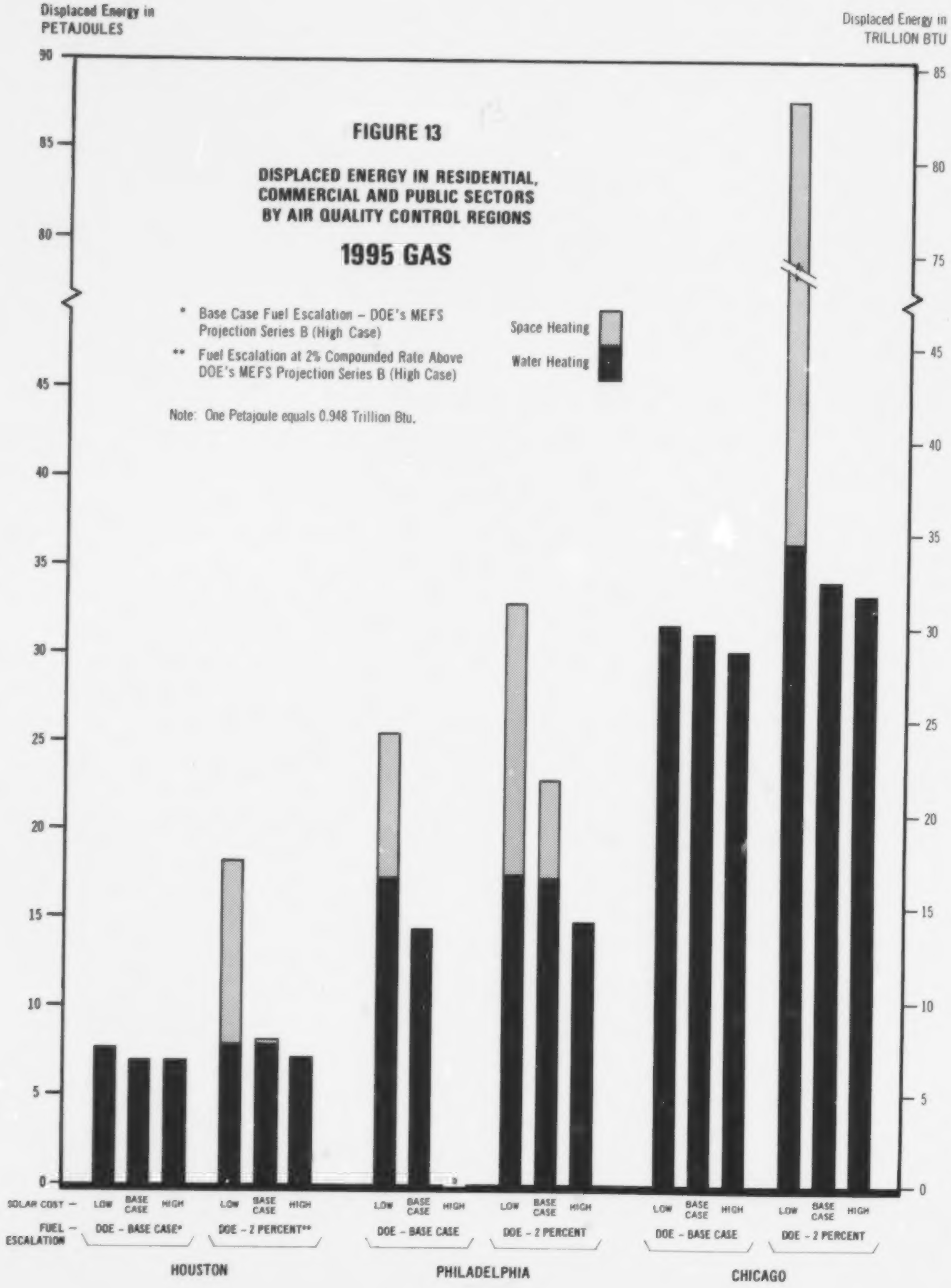


FIGURE 13

DISPLACED ENERGY IN RESIDENTIAL, COMMERCIAL AND PUBLIC SECTORS BY AIR QUALITY CONTROL REGIONS

1995 GAS

* Base Case Fuel Escalation – DOE's MEFS Projection Series B (High Case)

** Fuel Escalation at 2% Compounded Rate Above DOE's MEFS Projection Series B (High Case)

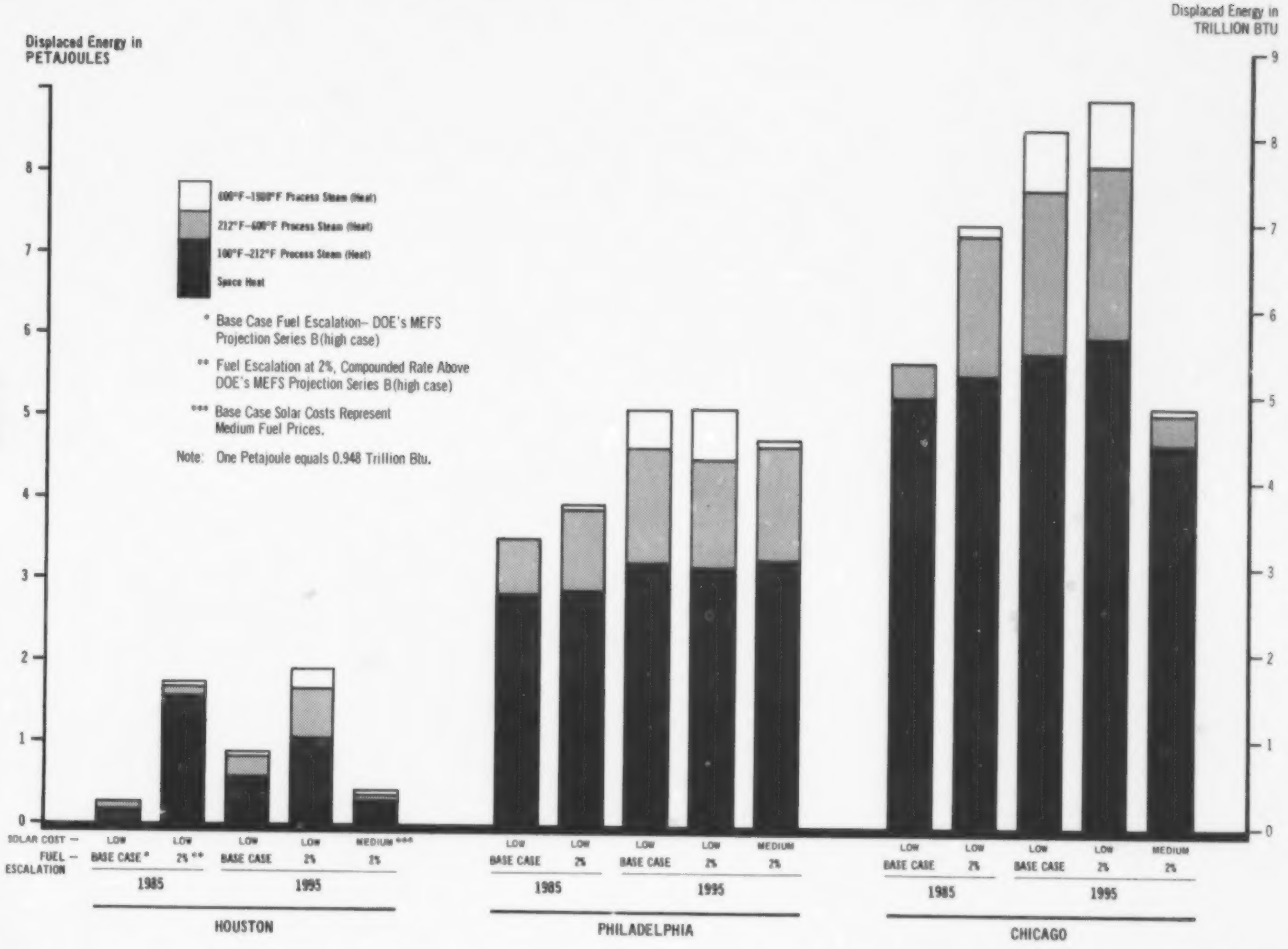
Note: One Petajoule equals 0.948 Trillion Btu.

Industrial Sector Results

Industrial fuel displacement increased under the three optimistic scenarios. (Figure 4). The change was reflected in competitive gas and oil space heat systems and competitive oil and gas process heat, steam applications, and preheat applications for temperatures up to 816°C (1500°F). The medium solar cost scenario (Scenario 5) produced no fuel displacement in 1985, just as was seen in the base case. However, when low solar costs were assumed (Scenarios 1 and 4), finite fuel displacements were observed. In 1995, finite fuel displacements were observed for all three optimistic scenarios.

However, the additional fuel displacement under the favorable solar scenarios did not significantly increase solar fuel displacement relative to the total industrial energy consumption base. Best case fuel displacement in 1985 amounted to 0.9 percent, 1 percent, and 0.1 percent of the total industrial energy consumption base for Philadelphia, Chicago, and Houston, respectively. Best case figures for 1995 for Philadelphia, Chicago, and Houston, are 1.3 percent, 0.9 percent, and 0.2 percent, respectively.

FIGURE 14
INDUSTRIAL FUEL DISPLACEMENT BY END USE AND TEMPERATURE RANGE



* Base Case Fuel Escalation– DOE's MEFS Projection Series B (high case)

** Fuel Escalation at 2%, Compounded Rate Above DOE's MEFS Projection Series B (high case)

*** Base Case Solar Costs Represent Medium Fuel Prices.

Note: One Petajoule equals 0.948 Trillion Btu.

SECTION 8

EMISSIONS DISPLACEMENT

The impact of active solar thermal systems on air quality is indirectly measured in this study as a reduction of emissions of particulates, sulfur oxides, carbon monoxide, hydrocarbons and nitrogen oxides in 1985 and 1995. Emissions reduction is a function of fuel displacement and of the emissions characteristics of the displaced fuel. Fuel displacement as a result of market capture by active solar thermal technologies and of the solar load fraction provided is presented in Section 7 of this report. This section translates fuel displacements into emissions displacements.

Emissions reductions will vary between AQCR's in part because the amount of emissions displaced depends not only on the market capture and solar load fraction but also on the mix of fuels displaced. Fuel combustion factors, which reflect the emissions associated with each fuel type, were obtained for the residential, commercial, public, and industrial sectors from EPA's AP-42 document (EPA, 1976). Emissions displacement from electric generation resulting from market penetration of solar technologies is a function of the total electricity displaced, the AQCR's utilities fuel consumption profile, regional SIP regulations where emissions are controlled (particulates, sulfur oxides, and nitrogen oxides) and of AP-42 emissions factors for uncontrolled emissions (carbon monoxide and hydrocarbons).

The emission reductions as a result of fuel displacement for the base case (mid-range solar cost and fuel price estimates) scenario are presented in Tables 25 to 29. In the first column of this series of tables, the total tons of emissions by pollutant displaced in 1985 and 1995 for each AQCR are presented and disaggregated by fuel type (as a percent of total displaced emissions). These percentages reflect the relative competitiveness of solar systems with different fuels as well as the emissions factors of the displaced fuel. For example, electricity displacement had the largest impact on emissions because solar was most competitive (in the majority of market segments) with electricity and electricity generally has higher emissions output than gas or fuel oil used in residences or commercial buildings. The Houston and Philadelphia AQCR's demonstrated this trend better than the Chicago AQCR because of Chicago's large nuclear generating capacity (estimated to be 60 percent by 1985), which tends to reduce total utility emissions output on a per kilowatt basis.

To put displaced emissions into perspective, the percentage of total emissions by source category has been calculated and is also presented in Tables 25 to 29. The 1985 emissions reductions were compared to total

TABLE 25. DISPLACED PARTICULATE EMISSIONS*

tonnes/year**
(tons/year)

Emission Source	HOUSTON Displaced	HOUSTON Percent of Total Emissions of Source Category***	CHICAGO Displaced	CHICAGO Percent of Total Emissions of Source Category***	PHILADELPHIA Displaced	PHILADELPHIA Percent of Total Emissions of Source Category***
1985 Total Tonnes	336.1 (370.6)	0.4	78.7 (86.8)	0.1	200.7 (221.3)	0.5
Percent						
Electric§	99	0.1	100	0.4	20	0.6
Gas§	0	0	0	0	0	0
Oil§	1	3.5	0	0	80	2.1
Industrial Gas	0	0	0	0	0	0
Industrial Oil	0	0	0	0	0	0
1995 Total Tonnes	371.5 (409.6)		365.7 (403.2)		346.0 (381.5)	
Percent						
Electric	76		17		32	
Gas	8		35		29	
Oil	1		48		27	
Industrial Gas	0		0		neg	
Industrial Oil	15		0		9	

* Base case (medium) solar cost scenario and DOE fuel price projection.

** 1 tonne = 1 metric ton = 1.102 short tons.

***Percentage of "source category" refers to the percentage of aggregate emissions for the residential, commercial, and public or industrial sectors for a given fuel type where solar systems are competitive.

§ Displaced emissions from residential, commercial and public sectors by fuel type.

neg = negligable.

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TABLE 26. DISPLACED SULFUR OXIDE EMISSIONS*

tonnes/year**
(tons/year)

	HOUSTON		CHICAGO		PHILADELPHIA	
Emission Source	Displaced	Percent of Total Emissions of Source Category***	Displaced	Percent of Total Emissions of Source Category***	Displaced	Percent of Total Emissions of Source Category***
1985 Total Tonnes	1237 (1366)	1.6	1495 (1648)	0.2	1140 (1257)	0.5
Percent						
Electric§	99	4.0	100	0.4	31	0.2
Gas§	0	0	0	0	0	0
Oil§	1	0.1	0	0	69	3.0
Industrial Gas	0	0	0	0	0	0
Industrial Oil	0	0	0	0	0	0
1995 Total Tonnes	2555 (2822)		1700 (1874)		2191 (2416)	
Percent						
Electric	96		70		15	
Gas	neg		neg		neg	
Oil	neg		30		83	
Industrial Gas	0		0		neg	
Industrial Oil	4		0		2	

* Base case (medium) solar cost scenario and DOE fuel price projection.

** 1 tonne = 1 metric ton = 1.102 short tons.

***Percentage of "source category" refers to the percentage of aggregate emissions for the residential, commercial, and public or industrial sectors for a given fuel type where solar systems are competitive.

§ Displaced emissions from residential, commercial and public sectors by fuel type.

neg = negligable.

TABLE 27. DISPLACED CARBON MONOXIDE EMISSIONS*

tonnes/year**
(tons/year)

Emission Source	HOUSTON Displaced	HOUSTON Percent of Total Emissions of Source Category***	CHICAGO Displaced	CHICAGO Percent of Total Emissions of Source Category***	PHILADELPHIA Displaced	PHILADELPHIA Percent of Total Emissions of Source Category***
1985 Total Tonnes	44.3 (48.8)	0.1	38.6 (42.6)	0.1	165.2 (182.1)	0.9
Percent						
Electric§	96	4.6	100	0.1	16	1.4
Gas§	0	0	0	0	0	0
Oil§	4	0.8	0	0	84	5.3
Industrial Gas	0	0	0	0	0	0
Industrial Oil	0	0	0	0	0	0
1995 Total Tonnes	128.7 (141.9)		373.9 (412.2)		393.9 (434.3)	
Percent						
Electric	44		8		6	
Gas	44		68		25	
Oil	2		23		65	
Industrial Gas	0		0		2	
Industrial Oil	10		0		1	

---

* Base case (medium) solar cost scenario and DOE fuel price projection.

** 1 tonne = 1 metric ton = 1.102 short tons.

***Percentage of "source category" refers to the percentage of aggregate emissions for the residential, commercial, and public or industrial sectors for a given fuel type where solar systems are competitive.

§ Displaced emissions from residential, commercial and public sectors by fuel type.

neg = negligable.

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(PREVIOUSLY EIN. EPA FORM 217)
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TABLE 28. DISPLACED HYDROCARBONS EMISSIONS*

tonnes/year**
(tons/year)

	HOUSTON		CHICAGO		PHILADELPHIA	
Emission Source	Displaced	Percent of Total Emissions of Source Category***	Displaced	Percent of Total Emissions of Source Category***	Displaced	Percent of Total Emissions of Source Category***
1985 Total Tonnes	10.2 (11.2)	0.6	13.6 (15.0)	0.1	98.2 (108.3)	1.8
Percent						
Electric§	90	5.3	100	0.9	12	1.2
Gas§	0	0	0	0	0	0
Oil§	10	0.5	0	0	88	5.1
Industrial Gas	0	0	0	0	0	0
Industrial Oil	0	0	0	0	0	0
1995 Total Tonnes	51.8 (57.1)		165.7 (182.7)		226.6 (249.7)	
Percent						
Electric	35		7		5	
Gas	44		62		8	
Oil	2		32		85	
Industrial Gas	0		0		1	
Industrial Oil	19		0		2	

* Base case (medium) solar cost scenario and DOE fuel price projection.

** 1 tonne = 1 metric ton = 1.102 short tons.

***Percentage of "source category" refers to the percentage of aggregate emissions for the residential, commercial, and public or industrial sectors for a given fuel type where solar systems are competitive.

§ Displaced emissions from residential, commercial and public sectors by fuel type.

neg = negligable.

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TABLE 29. DISPLACED NITROGEN OXIDE EMISSIONS*

tonnes/year**
(tons/year)

Emission Source	HOUSTON Displaced	HOUSTON Percent of Total Emissions of Source Category***	CHICAGO Displaced	CHICAGO Percent of Total Emissions of Source Category***	PHILADELPHIA Displaced	PHILADELPHIA Percent of Total Emissions of Source Category***
1985 Total Tonnes	1135 (1251)	0.7	261.2 (288)	0.1	998.7 (1101)	0.8
Percent						
Electric§	100	1.5	100	0.2	67	1.0
Gas§	0	0	0	0	0	0
Oil§	neg	0	0	0	33	2.0
Industrial Gas	0	0	0	0	0	0
Industrial Oil	0	0	0	0	0	0
1995 Total Tonnes	1760 (1940)		1858 (2049)		7030 (7751)	
Percent						
Electric	72		37		9	
Gas	12		52		15	
Oil	neg		11		74	
Industrial Gas	0		0		1	
Industrial Oil	15		0		1	

* Base case (medium) solar cost scenario and DOE fuel price projection.

** 1 tonne = 1 metric ton = 1.102 short tons.

***Percentage of "source category" refers to the percentage of aggregate emissions for the residential, commercial, and public or industrial sectors for a given fuel type where solar systems are competitive.

§ Displaced emissions from residential, commercial and public sectors by fuel type.

neg = negligable.

emissions data from the 1975 National Emissions Report (EPA, 1978) for all source categories in which solar was competed (e.g., residential and commercial fuel combustion and certain industrial processes). For example, in the Houston AQCR in 1985, use of active solar thermal technologies could result in the displacement of 336.1 tonnes per year of particulates, 99% of which could be from electric fuel displacement. This amount represents 13% of emissions from electric use in the residential, commercial, and public sectors in Houston (in 1975).* However, this reduction accounts for only 0.4% of the emissions from source categories where solar was competed.

Tables 25 to 29 also presents the emissions reductions in 1995 attributed to fuel displacement by solar systems. The increase in emissions reductions between 1985 and 1995 results from greater solar market capture in 1995. Solar systems become more competitive with fossil fuels over the longer timeframe. For example, the increase in the reduction of emissions of sulfur oxides and nitrogen oxides in Philadelphia from 1985 to 1995 is partly a result of solar capture of oil space heating and gas water heating markets in 1995.

The best case scenario (low solar cost and high fuel price projections) increased emissions displacement from 19 to over 700 percent over the base case scenario (See Table 30). The best case scenario offered the greatest emissions displacement in the 1995 timeframe where space heating and industrial process applications are captured but were not competitive under the base case. These high fuel-use markets were captured by solar under the best case scenario, greatly increasing the emissions impact. In the Chicago AQCR, for example, reduction of particulates emitted in 1995 jumps almost 300 percent with the capture of electric, gas and oil space heating markets cells in the residential, commercial, and public sectors under the best case scenario.

Most fuel displacement came from market capture by solar systems in the residential, commercial and public sectors. Oil and gas displacement in these sectors will result in emissions reductions from a diverse group of small sources rather than from point sources. These area source emissions reductions would tend to lower background levels, which may be desirable in an urban setting. Emissions displacement resulting from electric fuel displacement, however, will reduce utility point source emissions. The overall air quality impact of solar systems will depend on the emission trends (area versus point sources) in a given AQCR, on the population density, local meteorological conditions, and other factors.

As seen in Table 31, the overall impact of active solar thermal technologies on total emissions from all source categories in the base case

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*The comparison of 1985 emission reductions to 1975 baseline emissions data is done primarily to illustrate the overall magnitude of solar displacement. A forecast of 1985 and 1995 emissions was not within the scope of work in this study. A presentation of 1995 emissions reductions using 1975 as a baseline would present a very distorted picture of solar impacts and was therefore not attempted in this study.

TABLE 30. DISPLACED EMISSIONS RANGE, Tonnes/Yr (Tons/Yr)

	Particulates		Sulfur Oxides		Carbon Monoxide		Hydrocarbons		Nitrogen Oxides	
	Base Case	Best Case	Base Case	Best Case	Base Case	Best Case	Base Case	Best Case	Base Case	Best Case
Houston AQCR										
1985	336.1 (370.6)	441.8 (487.1)	1236.9 (1366.2)	1384.6 (1529.1)	44.3 (48.8)	84.6 (93.3)	10.2 (11.2)	27.5 (30.3)	1134.9 (1251.3)	1511.2 (1666.1)
1995	371.5 (409.6)	665.4 (733.6)	2555.4 (2821.6)	5008.1 (5530.8)	128.7 (141.9)	303.8 (334.8)	51.8 (57.1)	133.2 (146.9)	1759.3 (1939.7)	3640.4 (4013.7)
Philadelphia AQCR										
1985	200.7 (221.3)	1157.6 (1276.3)	1140.1 (1257.0)	2699.6 (2976.4)	165.2 (182.1)	561.0 (618.5)	98.2 (108.3)	310.2 (341.8)	998.7 (1101.1)	4028.1 (4441.1)
1995	346.0 (381.5)	1341.2 (1478.7)	2190.9 (2415.6)	2933.8 (3234.6)	393.9 (434.3)	731.0 (805.6)	226.6 (249.7)	389.3 (429.2)	7030.1 (7750.9)	8955.1 (9873.3)
Chicago AQCR										
1985	78.7 (86.8)	693.9 (765.0)	1494.7 (1648.0)	2882.2 (3177.7)	38.6 (42.6)	584.8 (644.8)	13.6 (15.0)	257.0 (283.3)	261.2 (288.8)	4164.9 (4591.9)
1995	365.7 (403.2)	1435.6 (1582.8)	1700.1 (1874.4)	3767.5 (4153.8)	373.9 (412.2)	1156.0 (1274.5)	165.7 (182.7)	537.1 (592.2)	1858.4 (2048.0)	7457.1 (8221.7)

NOTE: 1 Tonne = 1 metric ton = 1.102 short tons.

TABLE 31. TOTAL DISPLACED EMISSIONS AS PERCENT OF AQCR TOTAL*

1985 (tonnes/year)

Pollutant	HOUSTON Total Tonnes/year	 Percent displaced of total emissions**	CHICAGO Total Tonnes/year	 Percent displaced of total emissions**	PHILADELPHIA Total Tonnes/year	 Percent displaced of total emissions**
Particulates	336.1	0.2	78.7	<0.1	200.7	0.1
Sulfur Oxides	1236.9	0.6	1494.7	0.2	1140.1	0.3
Carbon Monoxide	44.3	<0.1	38.6	<0.1	165.2	<0.1
Hydrocarbons	10.2	<0.1	13.6	<0.1	98.2	<0.1
Nitrogen Oxides	1134.9	0.3	261.2	<0.1	998.7	0.3

* Base case scenario.

**Based on 1975 emissions data for all sources in a given AQCR.

in 1985 is less than one percent for each pollutant in each ACQR investigated. For example, the reduction in particulate emissions in Houston was 0.2 percent. Emissions reductions as a percentage of total ACQR emissions are low in part because of the large percentage of emissions in market segements in which solar is not competitive (e.g., certain industrial processes), or non-fuel combustion sources of emissions such as road dust. For example, while residential, commercial, and industrial fuel combustion yield 88 percent of area source SO_2 emissions in the Chicago AQCR, this is only 22 percent of all SO_2 source categories. Further, in the case of particulates, fuel combustion in these sectors in responsible for only 12 percent of all area source emissions. While solar-related emissions reductions will have a small impact on background emission levels, in many areas of nonattainment such as Chicago, point sources contribute a much greater percentage of emissions than do the source categories in which solar systems can compete.*

Despite the increase in emissions displacement under the favorable solar scenarios, displacement relative to total source category and AQCR emissions remained low. Displacement of emissions as a percent of source category emissions never exceeded four percent; as a percent of total AQCR emissions, displacement never exceeded 2 percent in 1985.

While these low percentages suggest the impact of solar systems on air quality may be limited, certain trends are evident. First, solar systems, particularly those in the residential, commercial and public sectors, reduce the emissions from a large number of small sources, lowering background levels. Small area sources of emissions are often located in high population areas (i.e., the residential sector) and are often more difficult to control using conventional strategies. Second, a generic study such as this analysis may overlook opportunities for greater solar market capture in specific locations or certain industrial applications. For example, cities such as Los Angeles, Denver or Phoenix may be better suited to solar systems (i.e., higher solar output) than the AQCR's investigated. Finally, in the market segments which solar captures, the solar system not only is competitive (i.e., cost-effective) with the fossil fuel system but also provides beneficial emissions reductions in the AQCR irrespective of their magnitude. This study suggests a limited impact on air quality by active solar thermal technologies, in Philadelphia, Chicago, and Houston. However, these results cannot be simply extrapolated for the nation as a whole, due to regional differences in energy prices, the historic-fuel mix pattern, and solar technical constraints.

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*Chicago AQCR data from Illinois EPA.

SECTION 9

POTENTIAL BIASES, LIMITATIONS AND GENERALITIES OF THIS STUDY

The results of this study indicate a limited potential for solar energy systems to affect total emissions levels in the timeframe and AQCR's investigated. This conclusion, however, should be qualified. There are a number of uncertainties associated with solar costs and future fuel prices, as well as with the effects of these variables on solar market capture. There are also simplifying assumptions that must be made in an analysis which is generic in scope. Given the structure of the analytic framework, assumptions must be qualified with several factors in mind: 1) potential sources of bias (both negative and positive towards solar) and 2) the generality of the results, given the technologies and regions evaluated.

POTENTIAL NEGATIVE BIAS

Residential and Commercial Load Assumptions

For a given economic scenario, fuel displacement was calculated assuming the least expensive (most optimally sized) system. In some cases, both the optimally sized system and the next to optimally sized system (usually a system meeting an intermediate fraction of the load) were competitive with the conventional fuel. Thus, the system meeting an intermediate fraction of the load could have been used, in these cases, in calculating fuel displacement. This would have resulted in a higher fuel displacement total.

It can be safely assumed that a consumer, given complete information and unrestricted choice, would opt for the least expensive system. However, conversations with solar installers indicate that current system sizing is often based upon other factors, such as the number of collectors that can be properly sited on the available roof space. System sizing in terms of an economic optimum is rarely a primary design goal. It is uncertain what sizing criteria will be used in the future as solar systems become more widely commercialized.

It was beyond the scope of the study to predict or assess actual installation procedures and consumer behavior. The fuel displacement total reflects the decision to use the least expensive system as a basis for calculating fuel displacement. An alternative approach would have been to use the system meeting the largest load fraction, provided the system was competitive. This would result in a higher fuel displacement figure (between 10-40 percent) than was determined.

Industrial Load Assumptions

The limitation of the potential solar fuel displacement base to 12 SIC's, based on load assumptions and process temperatures, was the critical factor in limiting solar energy potential in industry (particularly in Houston). However, specific applications at some process points in the "non-viable" solar industries might be viable and competitive. One example would be concrete block curing in the Stone, Clay, and Glass SIC (DOE, 1977). The limitation to those industries where solar energy systems are clearly more technically suited was a necessary simplification in this study as a means of specifying, quantitatively, industrial fuel displacement potential. This would underestimate fuel displacement potential to the degree that isolated point applications in the "non-viable industries," could adopt solar systems. Time did not allow an evaluation of all industrial processes in the engineering detail required to accurately measure the solar potential of all industrial process applications.

Range of Government Incentives

The sensitivity analyses evaluated a range of government incentives, spanning low to high levels of government support. Not all possible incentives were considered, however, nor were all possible ways of structuring the incentives evaluated. Other incentives include:

- Restructuring subsidies. A subsidy policy could be structured to make up the cost difference between the optimum sized system and less optimally sized systems meeting a larger load fraction. For example, tax credits and other subsidy measures could be made contingent on the requirement that a system meet a given load fraction (e.g., 75 percent for hot water heating, 50 percent for space heating). This policy could make the less efficiently sized systems meeting higher loads (and hence, displacing more fuel) more competitive than the optimally sized systems.

- Marginal cost pricing. Marginal cost pricing would significantly improve the competitiveness and market capture of solar energy systems. Replacement fuel costs are several times higher than average fuel prices (with the marginal costs rolled in). Solar hot water and heating systems are estimated to become very competitive under these conditions (Bezdek et al., 1979).

- Eliminating fuel deduction. The deduction of fuel costs as an operating expense penalizes capital-intensive alternatives (such as solar systems) because the present value of fuel deductions is significantly larger than the present value of deductions applying to capital equipment under various depreciation schedules. The deduction is equivalent to providing a 50 percent tax credit for conventional fuel burning (assuming a 50 percent marginal income tax rate). If the fuel deduction were eliminated, the relative economies of burning fuel versus installing a solar system would be altered in a direction favorable to solar. An alternative way of altering the relative economies would be to allow the deduction of the value of the fuel displaced by the solar system.

- Mandating solar systems. Federal, State, and municipal governments could require that solar energy systems be installed on (especially government-owned) buildings, regardless of solar costs. Since the decision would not be based on economics, any sized system (including a system providing the majority of the end-use load) could be stipulated.

With the exception of the restructuring subsidies incentive, the incentives policy measures are in varying degrees more extreme than the incentives evaluated in the analysis. Thus, while a range of government policies were included the analysis, they did not capture the effects of an strong pro-solar public policy.

POTENTIAL POSITIVE BIAS

There are a number of factors that were not considered that present the results in a favorable light. These factors should cancel in some measure the possible sources of bias noted above.

Alternative Technologies/Fuel Switching

It is a simplification to define solar fuel displacement potential strictly in terms of a cost comparison with conventional fuel-burning units. In reality, there are many alternatives that are less expensive than either solar or conventional fuel systems, including an array of conservation measures and, possibly, fuel switching.

- Conservation in the non-industrial sectors. A range of conservation measures may be employed to reduce operational building and appliance energy consumption that will compare favorably with a solar investment. Included are the use of heat pumps, insulation, and ventilation rate reductions.

- Conservation in industry. A range of industrial conservation measures may be more attractive than a solar investment. These include waste heat recovery, better process integration, process change, burning of plant refuse, etc. Several of the solar viable industries, including food and wood products, generate waste (wood chips, fruit pits, etc.) that can be burned. Evidence indicates that plants within these industries are moving in this direction (DOE, 1979). An example of technical process change has been introduced in the textile industry that may reduce solar low temperature process water potential. The change involves the substitution of a foaming process for wet processing. This saves 35 to 55 percent of the energy of that process step, or 21 percent to 33 percent of the industry's total energy (Carter, 1978). The process is easily retrofitted, requires a low level of capital expenditure, and offers a simple one and a half year payback.

- Fuel switching. It may be less expensive to fuel switch than to install a solar system. Currently, 15 percent, 9 percent, and 2 percent of the homes in the Federal regions encompassing Philadelphia, Chicago, and Houston use gas for either cooking or hot water heating but not space heating (AGA, 1977). It is a relatively simple matter to convert homes (or commercial buildings) with existing gas hookups to gas space heating systems. The possibility of converting fuel oil space heat systems to gas would reduce the market for solar systems.

Fuel switching to coal in industry has been encouraged by DOE policy and legislation (e.g., the Power Plant and Industrial Fuel Use Act (EEA, 1979)). Our industrial demand projections assumed a large degree of fuel switching and the solar fuel displacement base was narrowed to the degree that switching to coal was assumed. (Solar systems were not competitive with coal under any scenario).

There may be a number of technical and institutional constraints that limit the potential of conservation and fuel switching. Plant refuse is a dirty fuel and cannot be used for direct heat applications that require clean heat (for example, in food or textiles). It may not be possible to fully integrate process units to completely utilize waste heat. Gas may be in short supply, precluding a fuel-switching option. Not all boilers (particularly small boilers in the technical viable solar SIC's) are "coal capable" (i.e., can be retrofitted to coal use) (EEA, 1979). Thus, conservation and fuel-switching measures are not certain alternatives to solar energy systems. However, they must be considered in a realistic appraisal of solar energy potential.

Defined Markets

The solar markets, as defined, probably overestimate the potential solar displaceable energy base, because analysis of the detail required to further refine the markets in all relevant dimensions was beyond the scope of this study. Three cases where the potential base was probably overestimated are:

- Residential sector. The low income segment of the residential market will probably not install solar systems. The initial capital expenditure would be too large. (Marginal cost pricing and a well-publicized government program of low interest loan subsidies for solar systems might encourage the installation of solar systems in low income units).

- Waste heat recovery in industry. It was assumed that solar energy systems could potentially capture the entire low temperature energy base in those market segments where solar systems were competitive. This overestimates fuel displacement potential because, in many instances, waste heat is used to meet low temperature space heat and process needs. For example, in SIC 262 in Houston, 30 percent of space heat energy requirements are provided by waste heat recovery.* For SIC 286, 40 percent of the boilers provide 10 percent of the space heat load; 20 percent of the boilers provide 30 percent of space heat load; 20 percent of the boilers provide 50 percent of the space heat load; and the remaining 20 percent of the boiler population are mostly space heat boilers, providing 80 percent of the space heat load.* Similarly, waste heat is used to a significant degree in current industrial operations to meet low temperature process needs. Space heat and low temperature markets were not narrowed to reflect the practice of waste heat recovery, due to the difficulty in making quantitative generalizations. The degree of waste heat recovery varies greatly, depending on plant- and site-specific factors.

- Heat pump markets. To the degree that heat pumps have penetrated residential and commercial markets, the energy base would have been overestimated. It would be erroneous to assume that because solar systems were competitive with electric resistance heating, the entire electricity fuel base was displaceable. A fraction of the electric users are likely to be operating heat pumps against which solar systems might not be competitive. This fact probably affects the accuracy of the results less than the examples cited above, for two reasons: 1) the electric space heat market is not large and 2) the degree to which heat pumps have saturated the market does not appear to be high, although heat pump sales have been increasing. As of 1977, heat pumps were installed on 4.3 percent of all residential construction. In the southeast, the figure is 6.6 percent (DOC, 1977). This represents a small fraction of the total housing stock (new and existing) energy consumption. Heat pump market penetration is expected to be a more significant factor, however, in the 1985 and 1995 reference years.

Public Unfamiliarity: Institutional Constraints

No attempt was made to predict market penetration, as was described previously. Thus, it was not necessary to further narrow the displaceable energy base by incorporating institutional factors affecting the rate of solar market penetration. The theoretical displaceable base determined could have been severely underestimated and still suggest significantly more energy displacement than can practically occur.

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*From EPA NEDS data base.

GENERALITY OF RESULTS

The generality of results must be considered in perspective. Three factors possibly affecting the generality of the results are: 1) the solar technology/configurations evaluated, 2) the geographic location of the reference AQCR's, and 3) the markets excluded.

Solar Technologies

Several solar technologies were not evaluated in the analysis, including biomass, wind energy systems, photovoltaic systems, and central station electric generation of any type (either wind, photovoltaic, or thermal). Photovoltaic driven heat pumps, or photovoltaic cogeneration energy systems (where electricity is produced for building electric needs and waste heat is used for thermal needs) are applications with a potentially large fuel displacement. Additionally, the solar thermal configuration evaluated was intentionally kept simple to simplify the analysis procedure. Other configurations (optimized coupled storage systems, solar assisted heat pumps) were not evaluated. Caution should therefore be exercised in generalizing the results to all solar technologies. Further research is required to evaluate other technologies.

The Location of Reference AQCR's

The reference AQCR's probably are a fairly representative sample in terms of the structure of housing markets, commercial activity, and the structure of the industrial base. Fuel mix patterns may be reasonably representative. However, fuel prices and insolation profiles -- two factors affecting solar system economics -- are not representative of the whole country. Some parts of the country, such as the northeast, have fuel prices significantly higher than the AQCR regions evaluated; in other regions, such as the northwest, fuel prices are lower (for electricity). The southwest has a much higher insolation level than the reference AQCR's, while, in the northwest, insolation levels are somewhat lower.

Excluded Sectors

The mining, construction, and agricultural subsectors of industry were not evaluated, nor was the utility sector. With the exception of some parts of the agricultural sector (low temperature grain drying) these sectors are less likely near-term solar energy markets than the markets we evaluated and, in the aggregate, account for a fairly small share of total energy consumption. (Construction, mining, and agricultural accounts for 8 percent of the total national energy consumption.) The results of our analysis, therefore, do not reflect capture potential of these markets, and should not be generalized to them.

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APPENDIX A

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*Used in determining solar system costs in Section 6.

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APPENDIX B

SPACE COOLING FUEL DISPLACEMENT

Space cooling systems were found to be competitive in 1985 and 1995 under the more favorable solar scenarios. Fuel displacement potential of space cooling systems is hard to evaluate for reasons described below and was not calculated. However, some inferences can be drawn about the magnitude of space cooling fuel displacement.

Solar space cooling systems consist of a collector (flat plate or CPC) and an absorption chiller unit. The chiller unit, when not driven by solar energy, must be fired with gas. Currently, absorption chiller units are used in 10 percent of commercial buildings; residential absorption chiller units are commercially available, but rarely installed due to their expense relative to electric air conditioners.

Several factors are relevant in evaluating the fuel displacement potential of solar cooling:

1. Solar-assisted absorption cooling is not retrofittable, except in commercial buildings with existing units. A residential homeowner (or commercial building owner) would have to tear out the existing cooling unit and install an absorption chiller to retrofit solar space cooling. Thus, solar space cooling markets would be limited to 1) those commercial buildings (10 percent of the total) with existing units and 2) homes or buildings in which a new cooling system was being installed. This might include a new home or building, a building with an old air conditioning system up for retirement, or a unit not previously air conditioned. The difficulty in evaluating these markets was one of the reasons why solar cooling fuel displacement was not calculated.

2. Fuel displacement by solar-assisted absorption chillers displacing electric air conditioning (i.e., solar-assisted units installed in the new air conditioning market) probably would not greatly affect emissions, either on a per unit of installment basis, or in terms of overall sector emissions levels. Emissions effects per unit of installment will be a function of the different efficiencies of gas absorption and electric air conditioning units and the fraction of time the absorption system operates by solar energy. Gas absorption units operate at 50 percent efficiency, whereas electric air conditioning units have coefficients of performances of about 2.5. Combined with a 30 percent powerplant conversion and transmission efficiency, the efficiency of electric air conditioning units equals 0.75 (2.5 x 0.3). In short, to meet a load of one unit, an absorption chiller

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consumes two units of fuel, while an air conditioner consumes only 1.33 units. During those time periods when the absorption backup unit is operated for the solar cooling system, more fuel would be consumed than for an electric air conditioner. The overall effects on air emissions (on a per unit installed basis) would be a function of the fraction of time the solar system operated. Of course, gas burning produces fewer emissions than many powerplant fuel sources, so an emissions advantage of some degree probably would accrue with a solar-assisted chiller relative to electric air conditioning.

The second factor potentially limiting fuel displacement is the size of the new air conditioning unit market. The amount of energy consumed by new air conditioning units cannot be expected to be large relative to the sector total. This energy base would be narrowed further by the solar cooling load factor of approximately 20 percent.

3. The fuel displacement potential in the other market where solar-assisted chillers might operate -- retrofit to existing commercial chiller units -- also is relatively restricted. Cooling energy consumption for the Houston AQCR in 1985 is projected to be 37 percent of total commercial energy consumption. If 10 percent of this energy is provided by chillers, the potential solar fuel displacement base for solar-assisted chillers is 3.7 percent. If this market is completely penetrated, fuel displacement (assuming a 0.20 load factor) would be .74 percent of the sector total.

4. It should be pointed out that solar cooling units must be competitive not only with electric cooling but also with gas. Since gas is required as a backup fuel, gas (if available) would be used full-time for cooling, without a solar assist, unless the solar assist was less expensive than operating the gas unit. The RAR's calculated showed that solar was competitive with gas absorption cooling in several cases.

GLOSSARY

annualized solar cost: An economic term which represents the average yearly cost of a solar technology based upon capital and operating expenditures. Costs are "levelized" or turned into annual costs by use of discount rates.

area source: A term for emitters that can not be readily identified as a stationary source but that are associated with a specific geographic area. Examples of area source emitters include motor vehicles, residential heating furnaces, and gas station evaporative losses.

capacity utilization rate: The fraction of time a boiler or heater is operating. A capacity utilization rate of 0.45 means that the boiler/heater operates at capacity 45 percent of the time (or at less than capacity for an additional length of time equalling the same energy demand).

discount rate: An interest rate used to find the present value of a series of future cash savings or receipts.

levelized price: A series of uniform annual costs obtained by converting a stream of unequal annual costs to an equivalent present value over the system's lifetime

life cycle cost: The sum total of all costs associated with a capital investment over the lifetime of the project (or system)

load factor: A statistical term that expresses either (1) the percent utilization of a systems capacity or (2) the percent of an end-use demand satisfied by a energy system (such as solar)

net present value: The present equivalent worth of a series of annual cash flows taking into account the time value of money

nominal price: Price based on current dollars

payback period: The number of years required to acculmulate a cash savings equal to the value of the initial solar investment.

point source: Stationary facilities that are individual emitters of relatively large quantities of one or more air contaminants. A coal-fired power plant would be an example of a point source.

real price: Price based on constant dollars (zero inflation).